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DEPOSITIONAL HISTORY AND FAULT-RELATED STUDIES, BOLINAS LAGOON, CALIFORNIA

By

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DEPOSITIONAL HISTORY AND FAULT-RELATED STUDIES,

BOLINAS LAGOON, CALIFORNIA

By Joel R. Bergquist, U.S. Geological Survey

ABSTRACT

Studies of core sediments and seismic reflection profiles elucidate the structure and depositional history of Bolinas Lagoon, Calif., which covers 4.4 km^2 and lies in the San Andreas fault zone at the southeast corner of the Point Reyes Peninsula 20 km northwest of San Francisco.

The 1906 trace of the San Andreas fault crosses the west side of the lagoon and was determined from (1) tectonically caused salt-marsh destruction indicated by comparison of 1854 and 1929 U.S. Coast and Geodetic Survey (U.S.C. & G.S.) topographic surveys, (2) formation of a tidal channel along the border of destroyed salt marshes, and (3) azimuths of the trend of the fault measured in 1907. Subsidence in the lagoon of 30 cm occurred east of the San Andreas fault in 1906.

Near the east shore, seismic-reflection profiling indicates the existence of a graben fault that may connect to a graben fault on the Golden Gate Platform. Comparison of radiocarbon dates on shells and plant debris from boreholes drilled on Stinson Beach spit with a relative sea-level curve constructed for southern San Francisco Bay indicates 5.8 to more than 17.9 m of tectonic subsidence of sediments now located 33 m below mean sea level.

Cored sediments indicate a marine transgression dated at 7770±65 yrs B.P. overlying freshwater organic-rich lake deposits. Fossil pollen including 2 to 8 percent *Picea* (spruce) indicate a late Pleistocene (?)-Early Holocene climate, cooler, wetter, and foggier than at present. Above the transgression are discontinuous and interfingering sequences of transgressive-regressive marine, estuarine, and barrier sediments that reflect rapid lateral and vertical shifts of successive depositional environments. Fossil megafauna indicate (1) accumulation in a protected, shallow-water estuary or bay, and (2) that the lagoon was probably continuously shallow and never a deep-water embayment.

Analysis of grain-size parameters, pollen frequencies, and organic remains from a core near the north end of the lagoon indicates (1) that mid-nineteenth-century redwood logging correlates with rates of sediment accumulation of 1.3 to 1.9 cm/yr that are three to 6 times higher than post-1906 rates of 0.3 to 0.4 cm/yr, (2) accumulation of up to 115 cm of sediment since 1849, and (3) an anomalously coarse-grained sediment that may correlate with the 1906 earthquake.

INTRODUCTION

The origin and evolution of Bolinas Lagoon are of increasing interest because of its critical location in the San Andreas fault zone and alternatively because of concern over its ecologic well-being in the face of potential development. California coastal lagoons are few, and Bolinas Lagoon is one of only several that today exist in essentially pristine condition. The importance of Bolinas Lagoon as a spawning ground, bird sanctuary, and part of our natural heritage make it increasingly valuable as other California wetlands are destroyed. Much of the lagoon is now either Marin County park land or under the jurisdiction of the Audubon Society, and large areas of surrounding land are incorporated into the Golden Gate National Recreation Area and Point Reyes National Seashore.

The depositional history of Bolinas Lagoon has been a matter of speculation and conflicting ideas for nearly 100 years. Nearby redwood logging began in 1849 and resulted in increased sediment accumulation in the lagoon, the effects of which are alluded to by Munro-Fraser (1880) who wrote:

> ". . . When vessels first began to sail into the [lagoon], a schooner drawing ten feet of water could pass over the bar with ease at any stage of the tide, while now, the same draught of vessel can barely pass at the highest stage; and where those large vessels formerly lay at the wharf, the depth of water will not admit of more than a fishing smack. Old sailers are free to assert that the day is not far distant, at the present rate of filling in, when the entrance of the [lagoon] will be entirely closed, and the body of it will be mere tide and overflowed land open to reclamation and cultivation."

Ritter (1969, 1970, 1973) shows a sequence of maps purporting to demonstrate the development of islands and rapid shoaling of Bolinas Lagoon during 1858-1950 and discusses rapid siltation of the northern part of the lagoon following logging. Rowntree (1973, 1975) constructed a different sequence of maps that indicates the early existence of islands and extensive tidal flats, rejuvenation of the lagoon during the 1906 earthquake, and subsequent shoaling.

The period of time necessary to fill the lagoon naturally with sediment to the mean-sea-level datum is estimated to be 90 to 160 years and to the tighest high-water datum, 340 to 650 years (Ritter, 1973). Wahrhaftig (1970) estimated filling to the high-tide level in 500 to 2000 years.

This study determines: (1) the depositional history of Bolinas Lagoon, (2) the underlying structure, (3) vertical tectonic displacement, and (4) the effects of 19th-century logging on rates of sediment accumulation.

Acknowledgments

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Location, accessibility and culture

Bolinas Lagoon is located on the Pacific Coast in Marin County, Calif., approximately 20 km northwest of San Francisco (fig. 1). From U.S. Highway 101, the nearest thoroughfare, both California Highway 1 and the Panoramic Highway lead to Bolinas Lagoon. Highway 1 follows the eastern shore of the lagoon and continues north to Tomales Bay. The Bolinas-Olema Road leads south along the western shore of the lagoon to the small town of Bolinas. Stinson Beach, a community of comparable size, is situated at the southeast corner of the lagoon at the landward terminus of Stinson Beach spit. On the spit, a development known as Seadrift has been built.

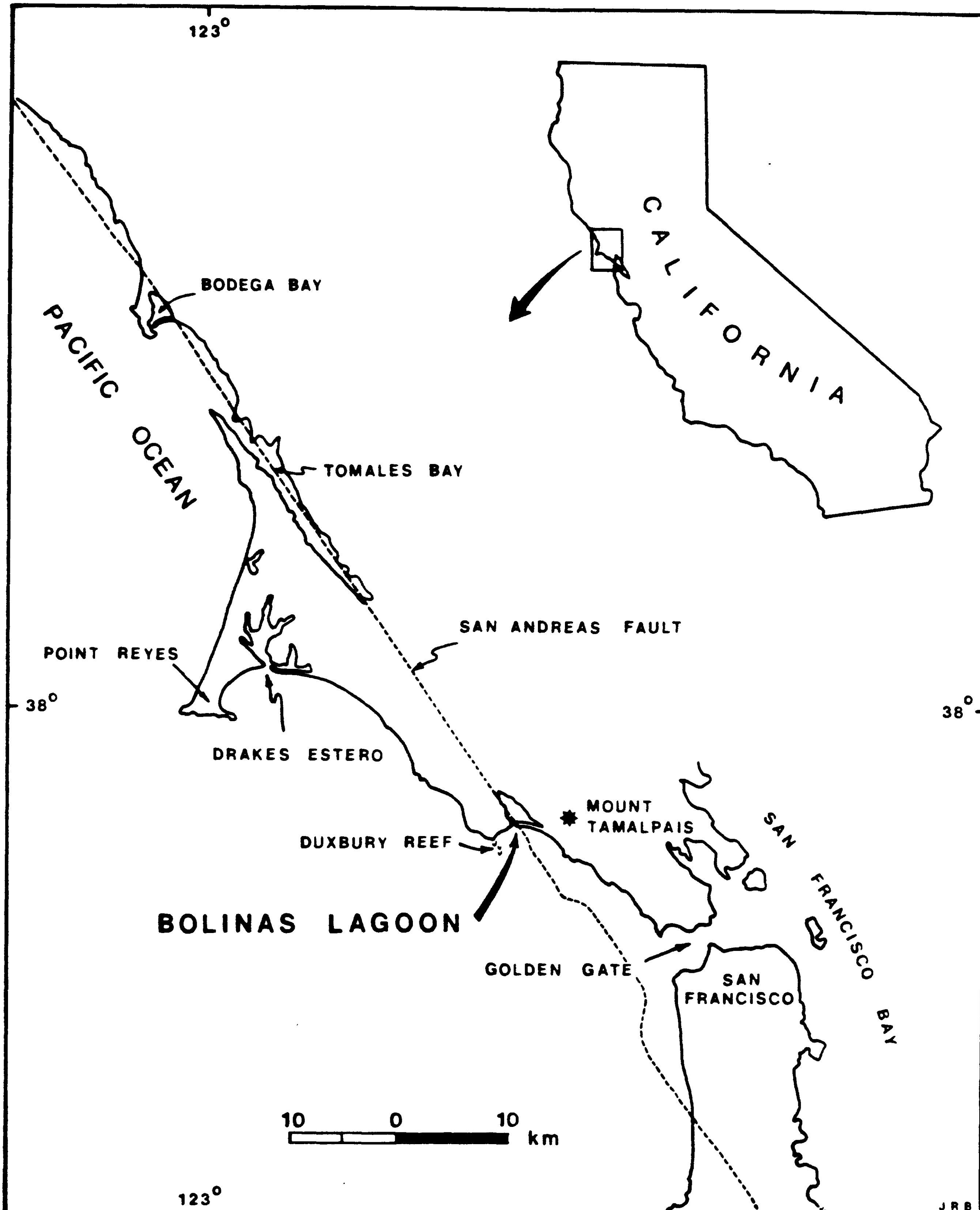

Figure 1. Index map showing location of Bolinas Lagoon in relation to other features along the northern California coast.

Much of the area in and around the lagoon is publicly owned. The western boundary of Point Reyes National Seashore is less than 2 km from the north end of the lagoon. Much of the land around the lagoon, including most of Kent Island, is owned by Marin County. The Audubon Canyon Ranch owns tracts of land in the lagoon and on the east shore, that it maintains as wildlife preserves. In 1972, lands east of the lagoon, except the Audubon property and Stinson Beach, were incorporated into the Golden Gate National Recreation Area.

Physical features

Bolinas Lagoon covers approximately 4.4 km^2, and is situated in the California Coast Range province which consists of northwest-trending mountain ranges that generally parallel the coastline. South of the lagoon is a youthful submergent coastline characterized by comparatively steep slopes that descend abruptly into the ocean. Northwest of the lagoon the submergent coastline is in a more mature stage, and wave-cut benches and cliffs characterize this part of the coast.

The most conspicuous and prominent topographic feature east of the lagoon is Bolinas Ridge, an elongate northwest-trending ridge that extends some 45 km from a point near the mouth of Tomales Bay to a point several kilometers south of Bolinas Lagoon. The ridge rises steadily from an elevation of approximately 150 m at the north end to over 600 m at the south. The remarkable flatness of the ridge when viewed offshore led to its 19th-century name, "Table Top Mountain." Several kilometers east of the southern end of Bolinas Ridge is Mount Tamalpais, the highest regional elevation at 793.7 m. Bolinas Ridge is dissected by numerous streams, many of which flow into the lagoon. Some of these are perennial, and others intermittent, flowing only during the rainy season.

The Point Reyes Peninsula is west of the lagoon and is geologically distinct from the mainland, though not topographically dissimilar. The highest elevations on the peninsula are Point Reyes Hill at 407 m and Mount Wittenberg at 428 m. The hills here, as on the mainland, are cut by numerous streams, which have incised steep-walled gulches and ravines. The part of the peninsula immediately north of Drakes Bay is an area of comparatively low relief and is the location of Drake's Estero, Estero de Limantour, and Limantour spit.

The extreme southeast margin of the Point Reyes Peninsula, Bolinas Mesa, is a broad flat area that extends 3 to 4 km from the hills that rise behind it. The mesa is an elevated remnant of a marine terrace, which, north of the town of Bolinas, has an elevation of approximately 60 m. The terrace gradually slopes toward Estero de Limantour where it reaches mean sea level (MSL). Numerous streams have incised the terrace on the top and margins. The marine terrace formerly was more extensive, but has been cut back by wave erosion. Duxbury Reef, a navigational hazard and unscheduled stop for many ships, is a wave-cut bench formed concomitantly with wave-induced cliff recession.

Between the conspicuous topographic high of Bolinas Ridge and the Point Reyes Peninsula lies the 1-km-wide San Andreas fault zone, which is topographically lower. The faulting and shearing within this zone has shattered and pulverized the rocks, making them susceptible to erosion, resulting in the characteristically low topographic profile of the fault zone. Numerous small hills elongated parallel to the direction of the fault occur in the fault zone and are small blocks or slivers that have been subjected to differential vertical movements. The low areas between these slivers often contain fault sag ponds or creeks. These creeks coalesce with those coming into the valley from the ridges to form the two major drainages in the fault zone. Olema Creek flows north into Tomales Bay, and Pine Gulch Creek flows south into Bolinas Lagoon. Pine Gulch Creek is perennial and is the largest stream flowing into the lagoon in terms of both volume of water and transported sediment. This creek enters the lagoon from the west and has built a delta. The delta prograded rapidly after the 1906 earthquake because of increased amounts of sediment contributed to the creek as the result of ground failure.

In addition to Pine Gulch Creek delta, there are smaller deltas at the mouths of creeks flowing into the lagoon from the north and east.

The 13-km lagoon shoreline is ringed by intermittent salt marshes, the largest of which occur (1) south of Pine Gulch Creek delta, (2) on Kent Island, and (3) in the extreme southeast corner of the lagoon, between the spit and the mainland.

Stinson Beach spit extends approximately 3 km from the eastern shore across the southern end of the lagoon and separates it from Bolinas Bay. The spit is separated from land on the west by an inlet approximately 50 m wide that varies in width depending upon tidal stage and season. In the mid-1960's, the lagoon side of the spit was dredged to form an extension for subdivision into lots for houses. Between this extension and the original spit, an aritficial lagoon was created. Kent Island lies north of the inlet and is largely above mean higher high water (MHHW). A smaller island known as McKennan or Pickleweed Island lies about 0.3 km from the east shore just south of the main tidal channel in the lagoon. This island is being eroded by the southeast migration of this channel. Other intersecting and anastomosing tidal channels of varying size cut through and drain marsh and mudflat areas.

Extensive areas of tidal flats occur between Pickleweed Island and Stinson Beach spit. Tidal flats north of Kent Island extend to the edge of the main tidal channel, which courses along the eastern margin of the lagoon. North of Pine Gulch Creek delta is the Upper Basin, most of which lies below mean lower low water (MLLW) and does not completely drain during normal tidal cycles.

Geologic setting

Bolinas Lagoon lies in the San Andreas fault zone at the southeast corner of the Point Reyes Peninsula (fig. 1). The 1906 trace of the San Andreas fault is near the west side of the lagoon (pl. 1) and apparently forms the western edge of a graben that underlies the lagoon. Seismic profiling indicates the existence of another fault along the east shore of the lagoon (pl. 1), which is assumed to be the east boundary of the graben (J. R. Bergquist, unpub. data). This fault may connect to a graben fault located offshore by Cooper (1973).

East of the San Andreas fault zone are rocks of the Late Mesozoic Franciscan assemblage including graywacke, chert, serpentinite, and spilite.

The Miocene Monterey Formation crops out almost exclusively west of the San Andreas fault zone, although faulted slivers lie within the fault zone between Bolinas Lagoon and Tomales Bay. The western three-fourths of the Point Reyes peninsula is Monterey Formation and is in near-vertical fault contact with the Pliocene Merced Formation, which forms the eastern side of the peninsula and borders the lagoon. In the fault zone, approximately 6 km northwest of the head of the lagoon, the Monterey lies in fault contact with Franciscan rocks. The Monterey Formation generally consists of poorly bedded, tan to gray mudstones, siltstones, shales containing sandstone lenses up to 50 cm thick and high-angle cross-cutting sandstone dikes (Gluskoter, 1969).

The Merced Formation lies almost wholly within the San Andreas fault zone and consists mostly of orange, buff, gray and brown, argillaceous, poorly indurated sandstones containing abundant fossils (Gluskoter, 1969). The faunal assemblages and gastropod/pelecypod ratios indicate the Merced Formation was deposited in the littoral zone of a sheltered, shallow marine basin (Glen, 1959), perhaps not unlike Bolinas Bay and Lagoon.

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USE OF MAPS FOR DETERMINING MORPHOLOGIC CHANGE IN BOLINAS LAGOON

Maps of Bolinas Lagoon are one source of evidence for historic changes in lagoonal morphology. Although many of the early maps that precede the first accurate survey[1] of the lagoon in 1854 are generalized, they yield some information on the large-scale features around the lagoon. The early maps are essentially valueless for quantitative comparisons, however, because most of them were drawn freehand with no horizontal or vertical control points. Numerous maps that include parts of the California coast were made during the Spanish colonial period. Only a few of these include coastal features identifiable as Bolinas Bay, and none is drawn with enough detail to enable even general descriptions of large-scale features around Bolinas Lagoon. Most of the early Spanish maps are small scale and show the bay as merely a small indentation, omitting the lagoon completely.

Hondius map of 1589

Proponents of Bolinas Lagoon as the landing site of Sir Francis Drake in 1579 argue that the Portus Novae Albionus (fig. 2) is a map of the lagoon (Neasham and others 1974; Neasham and Pritchard, 1974). This map, the Hondius map or Hondius broadside, was made by Jodocus Hondius (1589) about 10 years after Drake's landing and its exact location on the California coast has long been a subject of controversy. It was drawn from descriptions by a man who was not on Drake's voyage; this, coupled

Figure 2. Portus Novae Albionus, the Hondius map of 1589 depicting the Port of New Albion, possibly the first chart of Bolinas Lagoon. Original scale.

[1]The term survey refers specifically to the original field survey made with a planetable whereas map refers to printed reproduction of a compilation of one or more surveys published at a particular scale (Shalowitz, 1964).

with its sketchy quality, makes the map useless for morphological comparisons, even if it can be established that the map depicts Bolinas Lagoon. So far the evidence is dubious, but the map and its association with Bolinas Lagoon are historically interesting nonetheless.

Vancouver map, 1792

During the 1790's, Vancouver explored and charted the Pacific Coast from San Luis Obispo, Calif., to Alaska. A small-scale chart including Bolinas Bay was made in 1792 by Vancouver (fig. 3) and is quite accurate for maps of the time. It clearly shows Bolinas Bay and other coastal landmarks including Bodega Bay and the sandspit in front of it. The schematic depiction of terrain indicates the valley between Tomales and Bolinas Bays, through which the San Andreas fault cuts. At the south end of this valley, however, there is no indication of Bolinas Lagoon, although the shoreline follows the approximate position of the present-day spit.

Briones' Diseno, ca. 1841-42

Perhaps the earliest map of Bolinas Lagoon is the diseno (fig. 4) that accompanied Gregorio Briones' petition to the Spanish Governor for 2 square leagues of land. In Mexican California, settlers desiring land grants were required to submit a map or diseno describing as accurately as possible the requested land. Because there was no official government surveyor, each petitioner was responsible for having his map drawn (Becker, 1969). In 1841 or 1842, Briones had William A. Richardson, the grantee of Rancho Saucelito, draw the diseno (Mason and Barfield, 1973).

The diseno was presumably drawn freehand and not surveyed, judging from its stylized character as indicated, for example, by the double skyline. In addition to the lagoon, Pine Gulch Creek, the spit, and channel are clearly indicated. Interestingly, Pepper (Kent) Island and McKennan (Pickleweed) Island are not shown where they might be expected to occur. Nor is there any indication of a delta at the mouth of Pine Gulch Creek. The lack of these features on the diseno is not really significant though because the map contains a number of apparent exaggerations and incorrect features. The Bolinas Cliffs west of the channel appear to extend much too far south; Pine Gulch Creek is shown too far south; the distal end of the spit indicates a reversed curvature from its present form; and the channel is probably much too narrow. Because of the exaggerations and omissions, the diseno is of little value for comparative purposes.

Ringgold map, ca. 1849-50

The first published nautical chart that includes the Bolinas Bay area is by Ringgold (1852). Charts of San Francisco Bay were previously made by Capt. F. W. Beechey of H. M. S. Blossom in 1826-27 and subsequently published (Buckland, 1839), but the westernmost point on

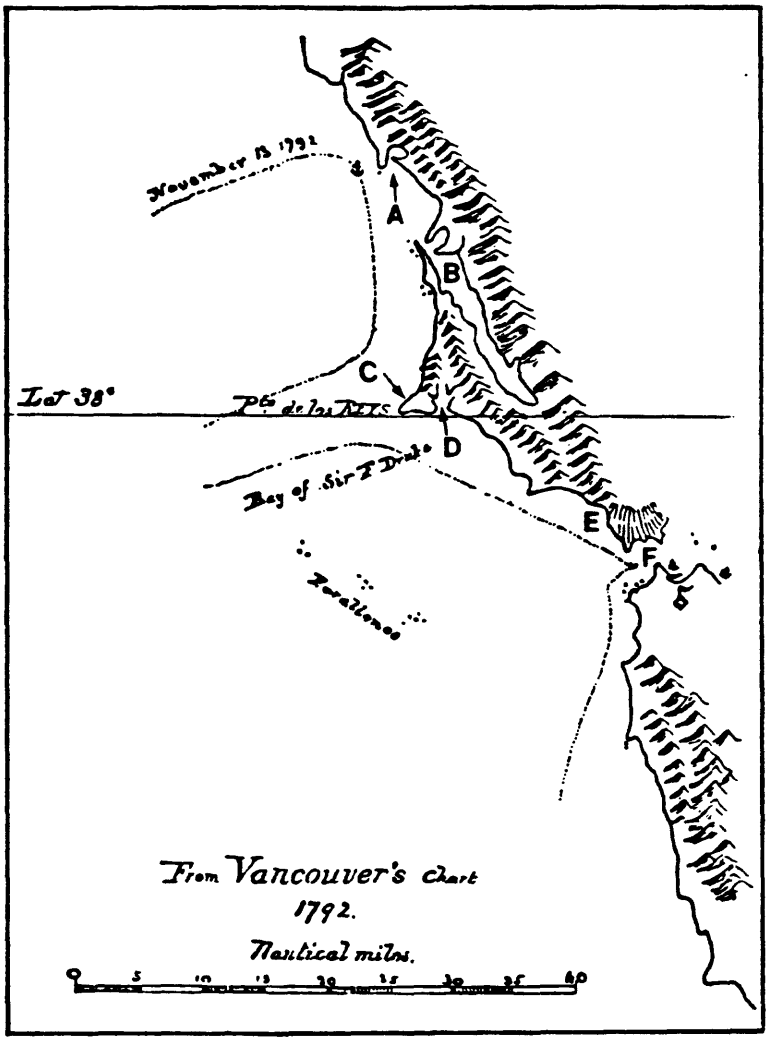

Figure 3. Part of chart by Vancouver, 1792, showing (A) Bodega Bay (B) Tomales Bay (C) Point Reyes (D) Drakes Estero (E) Bolinas Bay (F) Golden Gate. Bolinas Lagoon is not depicted. Original scale.

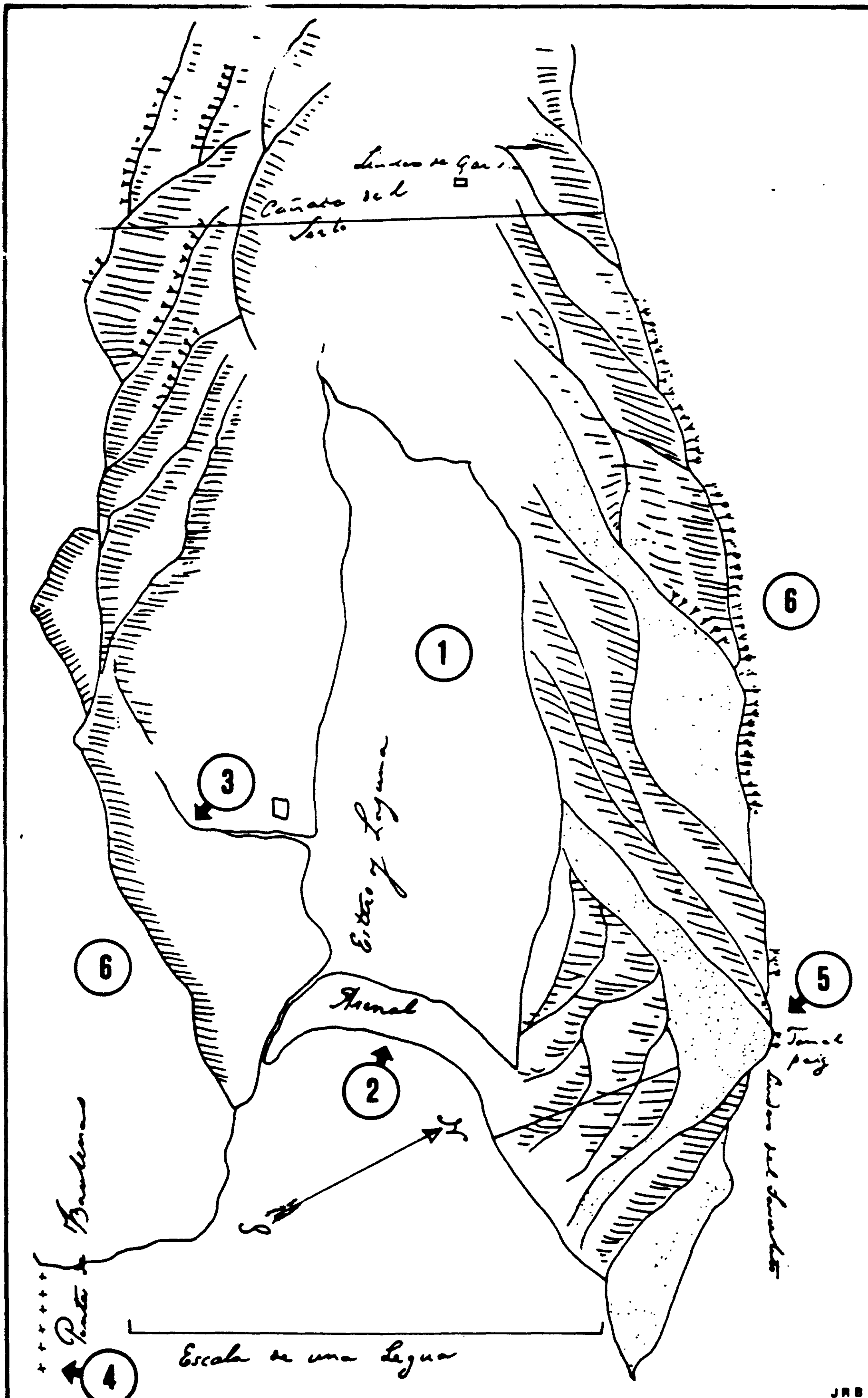

Figure 4. Diseño of Rancho Baulines by Wm. A. Richardson, ca. 1841-1842 showing (1) Bolinas Lagoon (2) Stinson Beach Spit (3) Pine Gulch Creek (4) Duxbury Reef (5) Mt. Tamalpais (6) double skyline. Figure adapted from Becker (1969).

the coast shown on these charts is near present-day Rodeo Lagoon. Bolinas Bay and Lagoon are not shown on the Beechey charts. Commander Ringgold, U.S.N., directed the 1849-50 surveys of San Francisco Bay and nearby navigable waters in response to the needs of an area besieged by gold-rush traffic and desperately in need of competent navigation charts. Toward this end, Ringgold set channel buoys, and surveyed shorelines and shipping channels within the bay by triangulation with quite accurate horizontal control. In San Francisco Bay, the Sacramento River and at selected points along the coast, careful hydrographic surveys were also made. Outside the Golden Gate, the shoreline was drawn as far north as Point Reyes, but was apparently drawn from sightings, and not surveyed. Part of Chart 1 (Ringgold, 1852) is shown in figure 5 and includes the area of Bolinas Bay presumably renamed "Rialto Cove" by Ringgold. Ringgold (1852) described the coastline:

> "Until reaching Duxbury Reef, (an extensive submerged ledge of rocks, running off in a southern line, its limit not yet thoroughly determined,) the north boundary of the entrance is clear and free from dangers. Bolenus Bay, now Rialto Cove, very frequently the safe resort of the hardy pilots, lies east of, and is formed by, the point and reef. Anchorage in five fathoms will be found, giving the reef a good berth, in rounding its south extreme."

The soundings, which range from 5 to 10 fathoms, indicate that Rialto Cove is present-day Bolinas Bay and not Bolinas Lagoon. The diseno drawn about 8 years earlier indicated the presence of a spit in front of the lagoon, and therefore Rialto Cove does not include the lagoon area prior to spit formation. Because Ringgold's purpose in measuring bathymetry in Rialto Cove was to provide information for anchorage, it can be speculated that had the lagoon offered adequate anchorage, it too might have been investigated instead of ignored. The lagoon is probably not shown on the chart because Ringgold spent little time surveying the outer coast. In his words: "I had desired to occupy the Farallones, and closely trace the shore line from Punto de los Reyes to the Golden Gate. Circumstances entirely prevented me from attaining so desirable a duty."

The maps made before 1854 were all approximately drawn, not surveyed or otherwise accurately drawn. In some cases, they contain enough detail to give indications of gross morphology; they cannot be used for detailed comparative work to elicit changes in geomorphology through time. For map and chart makers, Bolinas Lagoon seems to have been of little interest. Drakes Estero, Bodega Bay, and Tomales Bay all received more attention, probably because of their utility as anchorage. This suggests that in historic times Bolinas Lagoon was probably never deep enough to be a good port for ocean-going vessels.

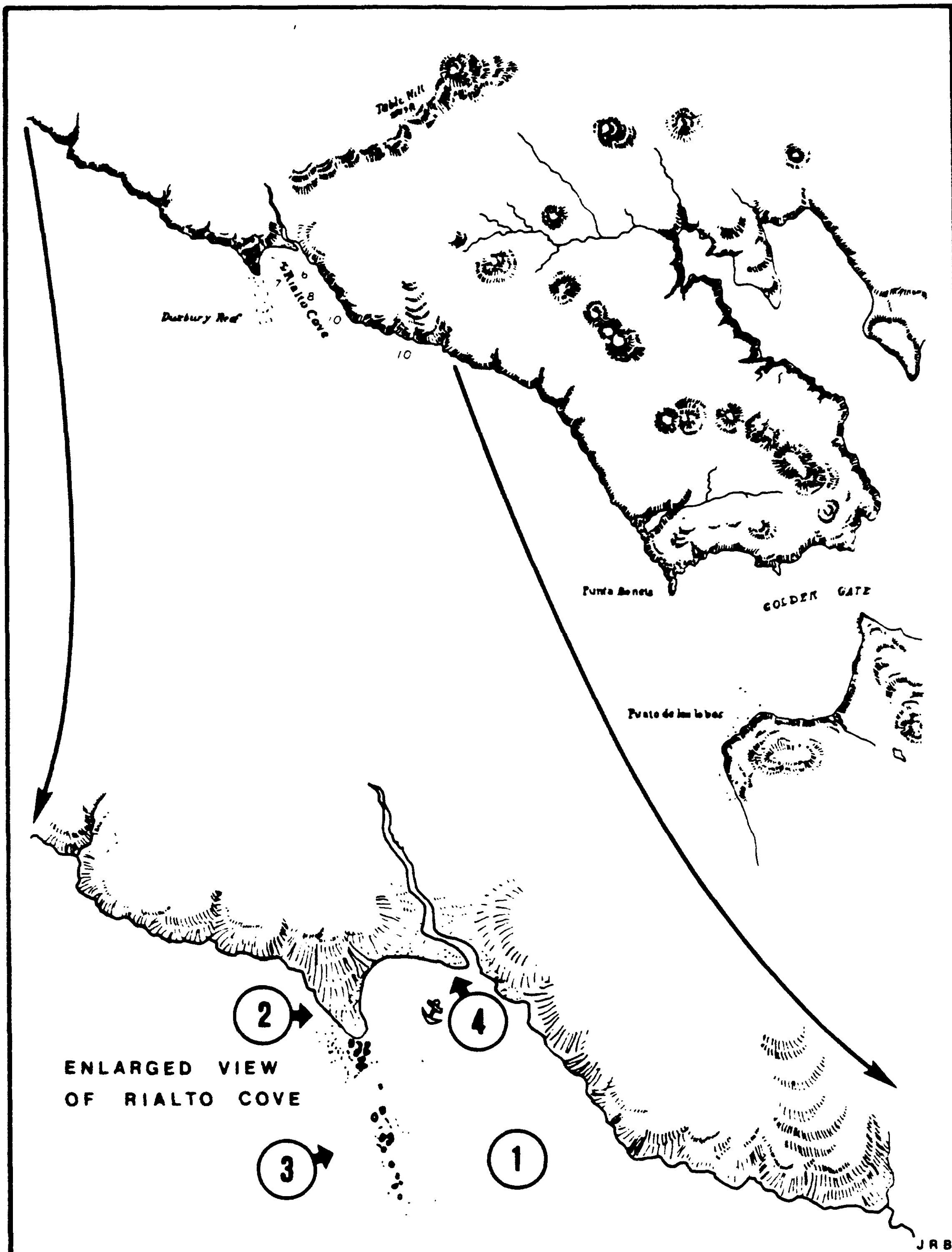

Figure 5. Part of nautical chart by C. Ringgold, U.S.N., ca. 1849-1850. Bolinas Bay shown as "Rialto Cove." Enlargement shows lagoon only by a sandy barrier breached at the east end by a small inlet. (1) Bolinas Bay (2) Duxbury Point (3) Duxbury Reef (4) sandy barrier. Adapted from Chart 1, Ringgold (1852).

U.S.C. & G.S. Topographic Survey

The U.S. Coast Survey published the first survey of the vicinity of Bolinas Lagoon in 1854, as part of its work on the California coastline (pl. 2, fig. 6, T452). This survey was made with good horizontal and vertical control. New control points, at maximum intervals of about 2.5 km, were tied into the existing network of triangulation stations. Geomorphic features including marshes, streams, dunes, and channels are clearly depicted in detail, unlike previous maps.

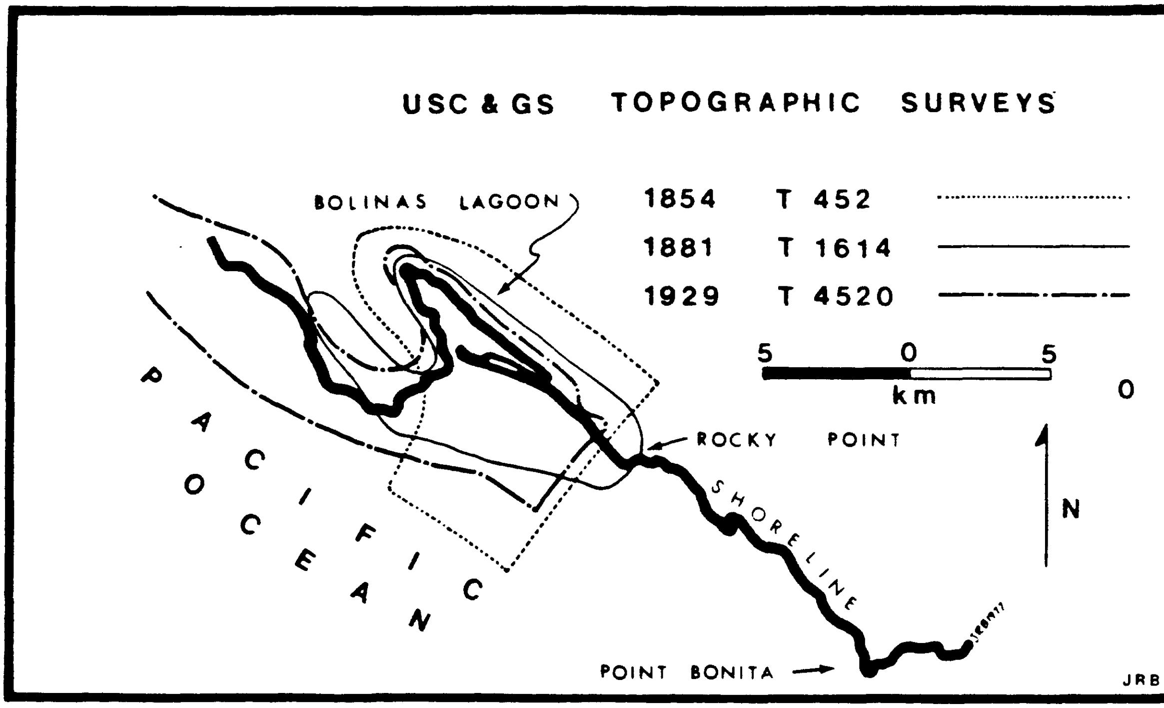

Figure 6. Outline map showing areas encompassed by U.S. Coast and Geodetic Survey topographic surveys that include Bolinas Lagoon.

In 1881, a second survey was done at Bolinas Lagoon by the U.S. Coast Survey (fig. 6, T1614), but only cultural features were updated; the configurations of geomorphic features were taken from the 1854 survey. If areas above mean high water (MHW) had changed markedly since 1854, this would presumably have been indicated. Because no major changes were made, the 1881 survey confirms the existence of large-scale features such as the islands.

In 1929 the lagoon was completely resurveyed for the first time since 1854, at a scale of 1:10,000 (pl. 3), the same as the 1854 survey. Geomorphic features including the shoreline configuration, which is the MHW line, changed significantly since the 1854 survey. The nature of the changes between 1854 and 1929 are subsequently discussed in detail.

U.S.C. & G.S. charts

From the 1850's to the present, the U.S. Coast and Geodetic Survey has published a series of nautical charts which include Bolinas Lagoon (U.S. Coast and Geodetic Survey, 1903-1939). The 19th-century charts are entitled "Entrance to San Francisco Bay, California," and later charts are simply "San Francisco Entrance, Calif." Under both titles, this chart was published in 38 editions between 1856 and 1971. The major sources of data for compiling these charts were the U.S.C. & G.S. Topographic and Hydrographic surveys, including T452 and T4520.

A series of San Francisco charts was examined by the writer at U.S. Army Corps of Engineers archives in San Francisco to determine morphologic changes in the lagoon during the past 115 years. Each edition of the chart included new data, though much of it was useful only for navigation, such as changes or additions to buoys, whistles, and lights. The chart was never completely resurveyed in successive editions; topographic or bathymetric changes were made only for local areas. Bathymetry indicated on the charts from 1856 to 1971 shows a nearly constant depth of 1 to 2 feet below MLLW at the seaward edge of the inlet between the spit and Bolinas Mesa and over the bar, which has formed in front of the inlet. The 1903 and 1915 charts (Fig. 7) show a depth of 10 feet at the north end of the channel, but in the 1939 chart (fig. 8), the depth at this point is shown as only 3 feet.

The large-scale features of Bolinas Lagoon depicted on the charts remained relatively constant from 1856 to 1929 and relied mainly on the 1854 topographic survey T452 (pl. 2) for configurations of geomorphic features. The interior of the lagoon depicted on a 1915 chart (fig. 7) is almost identical to the 1854 survey and gives no indication of large-scale morphologic changes on Pepper (Kent) Island resulting from the 1906 earthquake that were described by Gilbert (1908), although some minor changes related to cultural features are shown. For example, a road built on the west side of the lagoon, indicated first on the 1903 chart (U.S. Coast and Geodetic Survey, 1903-1939) resulted in minor changes in the marshes south of Pine Gulch Creek delta. Road construction on the east shore also caused marsh reduction there. From 1929 through at least 1941, the charts used updated data obtained from the 1929 Topographic survey T4520 (pl. 3). From the 1950's onward, the shoreline and interior of Bolinas Lagoon shown on various editions of Chart 5532 are generalized and much detail is omitted. The only features shown in the lagoon interior are parts of Kent Island above MHHW.

Relatively large-scale morphologic changes were not always made on successive editions of the chart, diminishing their value for comparative work. The appearance of a morphologic change in Bolinas Lagoon depicted on a chart only establishes a minimum age for that particular change. The date of a chart however does not necessarily correspond to the date of the actual morphologic changes that may have occurred much earlier.

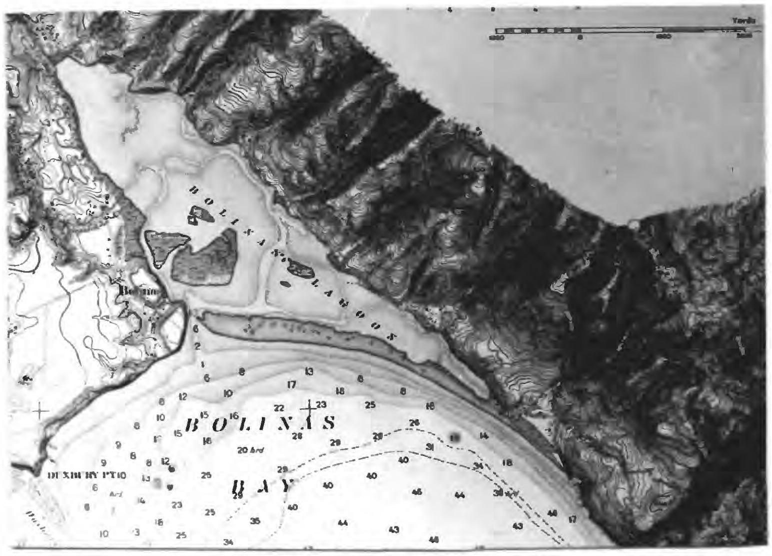

Figure 7. Detail from U.S.C. & G.S. Chart 5532, San Francisco Entrance, California, May 1915. Soundings in feet below MLLW. Original scale 1:40,000.

Figure 8. Detail from U.S.C. & G.S. Chart 5532, San Francisco Entrance, California, 1939. Soundings in feet below MLLW. Original scale 1:40,000.

Map sequences showing changes in morphology of Bolinas Lagoon

The assumption that the lack of islands in the lagoon on 19th-century maps reflected existing morphology has led to erroneous interpretation of the recent sedimentary history of Bolinas Lagoon. In conjunction with studies of sedimentation and hydrology in Bolinas Lagoon, Ritter (1969, 1970, 1973) published a sequence of four maps (fig. 9a), which supposedly show changes in lagoonal morphology from 1858 to 1950. The map sequence seemingly demonstrates a decrease in lagoonal area with the concomitant growth of several islands including Pepper (Kent) Island and McKennan (Pickleweed) Island.

The 1950 map, taken from the U.S. Geological Survey Mount Tamalpais 15′ topographic quadrangle, shows the shoreline at mean high water (MHW), and is presumably accurately drawn. The 1941 U.S. Army Corps of Engineers tactical map also may accurately show the configuration of the lagoon and islands, although it is not known whether the shoreline on this map represents a tidal datum. Different shoreline elevations on these two maps would affect the apparent size of the islands and shoreline configuration, and would mean the observed changes between the maps are not real.

The 1897 map taken from the U.S. Geological Survey Mount Tamalpais 15′ topographic quadrangle fails to indicate the islands in the lagoon, that in fact existed at the time the map was made, as evidenced by (1) their depiction on T452 (pl. 2), and (2) their description by Gilbert (1908).

The 1858 map (fig. 9a) was originally drawn as a plat of Rancho Las Baulines by R. C. Matthewson, October 1858, under the direction of the U.S. Surveyor General (Ritter, 1970). Comparison with the 1854 U.S. Coast Survey sheet T452 (pl. 2), which shows the islands, demonstrates that the 1858 plat was not surveyed, only generalized. Omission of the islands on the 1858 plat, therefore, is not evidence of their nonexistence.

The map sequence in Ritter′s model (fig. 9a) implies that the lagoon has been shoaling since 1858 and that the islands first appeared between 1897 and 1941. As shown by other map evidence, and by descriptions of islands in the lagoon in 1906 (Gilbert, 1908), this four-map sequence misrepresents the sedimentary history of Bolinas Lagoon.

The error of Ritter′s model was also recognized by Rowntree (1975) who prepared another four-map sequence to show evolving lagoonal morphology. The maps used in Rowntree′s model are: (1) U.S. Coast Survey topographic survey T452, (2) U.S. Coast and Geodetic Survey topographic survey T4520, (3) a map derived from a 1939 U.S. Army Corps of Engineers bathymetric survey, and (4) a map drawn from an aerial survey made by R. M. Towill Corp. in 1969. This sequence (fig. 9b) more accurately represents changes in lagoonal morphology.

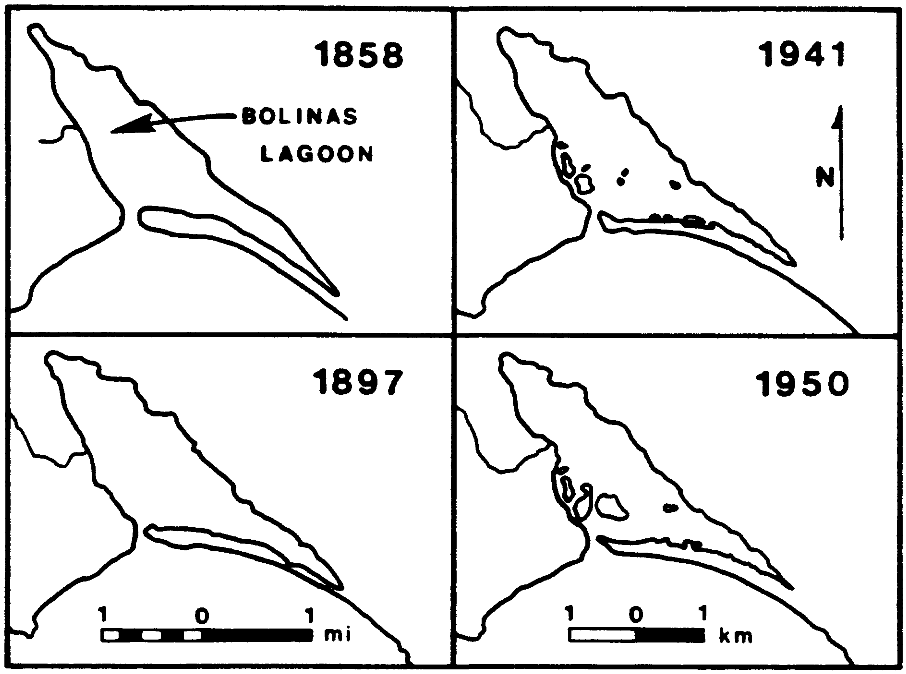

Figure 9a. Map sequence by Ritter (1969, 1970, 1973) indicating changes in Bolinas Lagoon. Figure adapted from Ritter (1973).

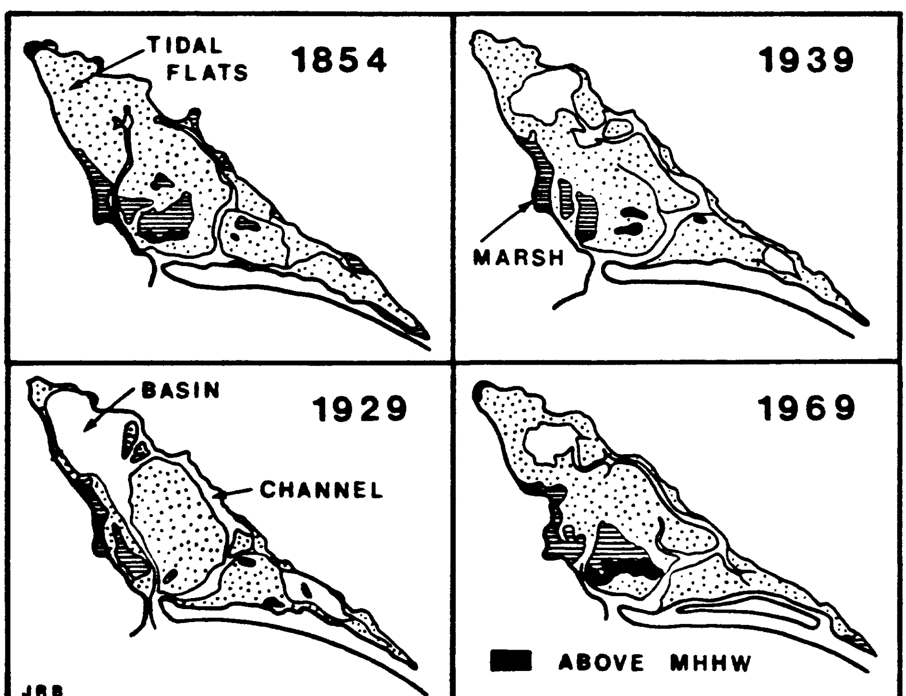

Figure 9b. Map sequence by Rowntree (1975) showing evolution of Bolinas Lagoon different from that by Ritter (1969, 1970, 1973). Analysis of a core for grain-size and pollen in this report indicates the north end of the lagoon in 1854 was probably subtidal, not tidal flats as shown here. Figure adapted from Rowntree (1975).

Several inaccuracies in the delineation of marshes, channels and tidal flats occur on some of the maps in Rowntree's sequence. The upper basin is shown on the 1854 map (fig. 9b) as tidal flats, and this apparently results from interpreting a generalized drainage pattern on the 1854 U.S. Coast Survey sheet (pl. 2) as a surveyed dendritic tidal-flat drainage channel, which it probably is not. Evidence, discussed in detail in a later section, from analysis of a core taken in the margin of the upper basin indicates 110 to 115 cm of sediment accumulation there since 1849, when redwood logging north of the lagoon was started. Taking into account possible downdrop of as much as 30 cm in this area during the 1906 earthquake (Gilbert, 1908), the bottom of the lagoon would have been at least 80-85 cm lower than at present and therefore probably subtidal basin rather than tidal flat.

The channels on the 1854 survey are delineated by the MLLW lines, but the lack of these in the upper basin should not necessarily be used as evidence of shoal conditions there because (1) the MLLW lines were not always completely drawn on early U.S. Coast Survey sheets, and (2) the positions of MLLW lines on the topographic surveys were estimated by topographers (Shalowitz, 1964). The hydrographic surveys are the authoritative sources for data below the high water plane (Shalowitz, 1964). T452, a topographic survey, is thus reliable only for features above the plane of high water, and conclusions based upon quantitative analyses of areas below this plane on the topographic surveys are tenuous. The early hydrographic surveys by the U.S. Coast Survey in the vicinity of Bolinas Lagoon indicate no bathymetric data for the lagoon itself and are limited to the inlet and offshore areas. Hydrographic surveys H-456 made in 1855 and H-721 made in 1858-60 show depths near the bar in front of the lagoon inlet, but not behind this area. Apparently no accurate 19th-century bathymetric data exist for the lagoon.

The 1939 map, done by the U.S. Army Corp of Engineers (Fig. 9b), is essentially a hydrographic survey, and the indicated areas of marsh and tidal flat are approximations because they were not accurately delineated on the original map. The 1969 map (fig. 9b) is drawn from aerial photography without ground-elevation controls, and the landward edge of the marsh is only approximated. This map also fails to show the Pickleweed Island marsh, which has existed at least since 1854.

Quantitative comparisons of increases or decreases in areas of marshes, channels, and tidal flats based upon these four maps must therefore be considered approximations because of (1) misinterpretation of original surveys, and (2) the approximate locations of marsh-upland boundaries and MLLW lines on the original surveys.

Comparison of 1854 and 1929 topographic surveys

Composites of the 1854 U.S. Cost Survey topographic survey T452 and the 1929 U.S. Coast and Geodetic Survey topographic survey T4520 were made to provide accurate visual comparison of changes in the morphology of Bolinas Lagoon and to locate the 1906 trace of the San Andreas fault.

The 1854 and 1929 surveys were accurately drawn within certain limitations described below. They are the only comprehensive surveys made of Bolinas Lagoon and the surrounding area, and because they are separated by a significant time span, can be used to document changes in lagoonal morphology.

The 1854 survey T452 (pl. 2) was published approximately 5 years after large-scale redwood logging began in the hills around the lagoon. Evidence from a core taken in the north end of the lagoon, discussed in a later section of this paper, indicates a relatively rapid influx of sediment resulting from damage to the watershed caused by logging operations. Although changes in morphology subsequent to 1854 can be determined from map comparisons, the problem of whether the 1854 survey reflects changes wrought by sediment accumulation after the inception of logging in 1849 is an unanswered question largely because, as discussed previously, earlier maps are of little help in determining morphology of the lagoon prior to 1854. T452 is the only survey of the lagoon made before the 1906 earthquake, and T4520 is the first post-1906 survey. Comparison of these two surveys thus offers the best available topographic evidence for morphological changes in the lagoon caused by the 1906 earthquake. The surveys, in conjunction with descriptions by Gilbert (1908), can be used to determine the 1906 trace of the San Andreas fault through part of the lagoon. Comparison of the two surveys shows, in addition to tectonically induced changes, cumulative morphologic changes from 1854 to 1929 in (1) marshes, (2) channels, (3) cliffs, (4) shoreline, (5) Pine Gulch Creek delta, and (6) the spit.

Methods and accuracy of surveying

The U.S. Coast and Geodetic Survey sheets T452 and T4520 were made as part of a general survey of the United States coastline, which began as early as 1807 when Thomas Jefferson persuaded Congress to adopt a resolution for a "Survey of the Coast" (Shalowitz, 1964). The purpose of the survey was to delineate accurately the coastline including islands within 20 leagues (60 nautical miles) of the shore primarily for the purpose of producing nautical charts. The California coast survey began around 1850, the date of California's admission into the Union. The first areas surveyed included Monterey Bay and the major harbors, San Francisco and San Diego. The surveys moved out from these points, up and down the coast.

Before the use of aerial photography in the 1920's, the surveys were made with planetable and alidade. Before 1880, ground distances were measured by chaining. For places inaccessible to chainmen, and large extents of sandy and marshy coast, the map linework was sketched. After 1880, the stadia rod was used to determine distances optically (Shalowitz, 1964). Thus, on the 1854 survey, distances were measured by chaining; and on the 1929 survey by use of the stadia rod, a more accurate method.

For shoreline mapping, standard practice was to set the planetable at a prominent point with a view of a least 400 meters, the minimum distance between measured points as outlined in instructions to topographers (Shalowitz, 1964). The rodman walked the shoreline, stopping at suitable intervals for fix points at which time the topographer plotted the azimuth and distance. The shoreline was subsequently sketched between the fix points. Unless the fix points are indicated on the surveys, there is no way of recovering them, and there is no way of determining the measured points on a given shoreline. Fix points are not indicated on either T452 or T4520. Usually the salient shoreline points were located accurately and the concave portions of the shoreline or bights were sketched.

Accuracy of 19th-century surveys including T452 is generally quite good because they were mapped at relatively large scale (often 1:10,000) and because they were based on a geodetic network, which minimized the possibility of accumulating large errors.

High-water line

The boundary between land and water on the surveys is delineated by the line of MHW. Accurate determination of this line would have involved detailed spirit-levelling along the coast, but for purposes of constructing navigation charts, the investment of time and effort required by such painstaking work was not justified, hence not done. In practice, the MHW line was determined by reference to the line of drift left by the preceding high water. On the Pacific Coast, where there are unequal high tides, there are often two lines of high water drift, and the MHW line was drawn somewhere between them (Shalowitz, 1964). The accuracy of shoreline delineation done by this method is somewhat variable depending upon the type of shoreline surveyed and the skill and care of the topographer, but Shalowitz (1964) indicates that these lines are generally horizontally accurate within 10 m of their true position. The figure of 10 m includes the cumulative effects of (1) the normal 1-m control in measuring distances, (2) the determination of the planetable within 2 to 3 m of its actual position, and (3) the error attendant in determining the position of the MHW line on the ground. Also, the 10-m accuracy refers to the location of the fix points but does not include the error inherent in sketching the shoreline between fix points, which may result in linework more than 10 m in error. Because of triangulation control, however, no large errors were allowed to accumulate, and general accuracy remained within the above limits. The relative accuracy of the MHW line makes it generally acceptable for large-scale quantitative work, although the fact that it is sketched between rod stations or fix points must be kept in mind.

Low-water line

Both the 1854 and 1929 surveys show a dotted low-water line (pl. 2, 3; figs. 7, 8). On the Pacific Coast, this represents the topographer's estimate of the MLLW line rather than mean-low-water (MLW) line (Shalowitz, 1964). The reason for this is that topographic surveys were intended for compilation into nautical charts which used the MLLW line as a plane of reference. The position of the MLLW line on the Pacific coast surveys is generally only an approximation of its true position inasmuch as U.S. Coast Survey topographic surveys were made primarily to delineate the high-water line. The MLLW line was not always shown, but if so, it was often incidental to the survey and served merely as a guide for subsequent hydrographic surveys (Shalowitz, 1964).

The MLLW line on the 1854 survey was presumably done according to the instructions to topographers issued about 1840, which directed that the proper time for determining the low-water line was "a couple of hours before the end of the ebb and the same time during commencement of the flood tides" (Shalowitz, 1964). Two hours on either side of a low tide could shift the water/land interface considerably, especially on gently sloping tidal flats, and the resultant map line would not then truly represent the intersection of a tidal plane with the land. Hence, the survey MLLW line is only an approximation and not accurately positioned.

The topographers of the 1929 survey, T4520, may have followed the instructions given in a 1928 topographic manual (Swainson, 1928) which directs that "the low-water line [should be located] so far as the latter can be determined or estimated without waiting for low tide." This is a clear mandate for an approximation. Some topographers surveyed points on the MLLW line, but no distinctions are made between surveyed and sketched lines; therefore, the MLLW line for a given map must be considered an approximate position of the line and not an accurate delineation.

The fact that MLLW lines on the topographic surveys made by the U.S. Coast and Geodetic Survey, including T452 and T4520, are only approximately located makes them unsatisfactory for use in quantitative comparisons of a given location through time. Nevertheless, the MLLW lines are very useful for comparisons of their relative positions through time in a given area, provided that small irregularities and minor changes are ignored.

Marsh areas

The MHW line was not usually determined for shoreline marsh areas because the physical characteristics of marshes make that line difficult to determine with any degree of accuracy. Shalowitz (1964) states that unless there is evidence to the contrary indicated on the survey, it must be assumed that the MHW line was not determined in marsh areas.

Instead of the MHW line, the outer or seaward edge of the marsh was surveyed, and there is no way to determine elevations of marsh areas relative to tidal datums[1] on the topographic surveys.

The inner edge of the marsh on the 1929 survey is indicated simply by truncation of the marsh symbol (pl. 3) and not by a drawn line. This indicates the dividing line between marsh and upland and bears no relationship to any tidal datum, except that areas shoreward of this demarcation are generally above the highest tides (Shalowitz, 1964). Instructions to topographers (Swainson, 1928) indicate that the inner edge of a marsh when clearly defined on the ground may be drawn by a line distinctly lighter than the MHW line. The absence of such a line on T4520 at most implies that the marsh/upland boundary was indistinct or transitional.

On the 1854 survey, the inner edges of the marshes are indicated by a thin line. This does not necessarily imply greater accuracy than the unlined position shown on the 1929 survey T4520, but merely implies that the topographers distinguished marsh and upland areas. The line drawn at the landward marsh boundary does not necessarily correspond to a tidal plane, although on some surveys it may partly or entirely coincide with the MHW line. The accuracy of the position of the inner edge of marshes often depended upon accessibility, and there was a tendency for topographers to generalize this feature. Thus for surveys such as T452 and T4520 the position of the outer edge of the marsh was rendered with perhaps the accuracy of the MHW line, whereas the inner edge of the marsh may have been merely approximated. This permits quantitative comparisons of the outer edge of the marsh through time but restricts the utility of the inner marsh edge for similar purposes. Because of this, quantitative comparisons of marsh areas on successive maps will also be only approximations. Where no inner edge of a marsh exists, as on Pepper (Kent) Island and McKennan Island, quantitative comparisons of marsh area will of course be tenable.

Horizontal control on 1854 and 1929 topographic surveys

The North American 1927 Datum is the geographic or geodetic datum presently in use as the basis for computation of horizontal control for surveys in which the curvature of the earth is considered. The reference point or triangulation station for this datum is in Meades Ranch, Kansas, and is defined by latitude and longitude coordinates on the Clarke Spheroid of 1866 (Shalowitz, 1964). This is now the point to which all features in the horizontal plane must be referred in order to make accurate comparison. In short, the position of the Meades Ranch station and one azimuth from that point determine the latitude and longitude net for North America. This net must itself refer to the

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[1] In geodetic work, datums is the accepted plural of datum where the meaning of the term is geometrical rather than statistical (Shalowitz, 1964).

approximate shape of the surface of the earth, but because the geoid is such an irregular surface, it was determined nearly 200 years ago that a geometrical surface was needed for systematic horizontal control of points on the globe. For geodetic work, the two most important geometric surfaces devised were the oblate spheroids termed the Bessel Spheroid of 1841 and the Clarke Spheroid of 1866. Each of these spheroids approximates the shape of the earth with the minor axis coinciding with the axis of rotation. The Clarke Spheroid of 1866 is slightly larger and based upon more precise calculations than the Bessel Spheroid of 1841. The U.S. Coast Survey used the Bessel Spheroid of 1841 between 1844 and 1880 at which time the Clarke Spheroid of 1866 was adopted (Shalowitz, 1964). Despite the existence of a more accurate spheroid, the International Spheroid of Reference, the Clarke Spheroid of 1866 is still used for work in North America largely because of economic reasons. Converting to a different spheroid would necessitate recomputing all existing triangulation with no real advantage to geodetic or cartographic work (Shalowitz, 1964).

The changes in the position of latitude and longitude lines on maps prior to 1927, the date of adaptation of the present geographic datum, are the result of (1) changes in the spheroid of reference, (2) changes in longitude values, and (3) changes in the geographic datums (Shalowitz, 1964). On the 1854 survey (pl. 2) several sets of projection line intersections (tick marks) are drawn. The last set of projection lines were plotted on T452 in 1914, and represent the United States Standard Datum on the Clarke Spheroid of 1866. A second set of projection lines on T452 were plotted northeast of the United States Standard Datum lines. A notation on T452 cropped from the area of plate 2 indicates that this set of lines was "based on Clarke's Spheroid" and added in 1904. The geodetic datum which formed the basis for these lines is not known. The United States Standard Datum had been adopted as early as 1901 (Shalowitz, 1964), yet if this set of projection lines were based upon the United States Standard Datum on the Clarke Spheroid of 1866 it would coincide with those added in 1914 discussed above. The fact that they do not coincide indicates that the 1904 ticks are based upon an independent datum. A third set of projection lines, which lies between the sets added in 1904 and 1914 is of unknown origin, but archaic printing on some of the lines cropped from plate 2 suggests that these were added at an early date, and they may be the original projection lines of an independent geographic datum on the Bessel Spheroid of 1841.

The 1929 survey T4520 (pl. 3) has only one set of projection lines corresponding to the North American 1927 Datum on the Clarke Spheroid of 1866.

Mechanics of compositing surveys

Plate 4 with linework from both the 1854 and 1929 surveys was photographically composited. Prior to compositing, the two surveys and the modern base map were brought to scale by measuring distances between selected points on each map, computing enlargement factors, and rephotographing each of the original base maps -- 1854, 1929, and 1971. The original publication scale of both the 1854 and 1929 maps was 1:10,000, and was retained in this study because it is a metric scale and because it shows the detail of the originals.

Stable-base cronaflex copies of the 1854 and 1929 surveys were obtained from the U.S. Coast and Geodetic Survey (NOAA) archives in Washington, D.C. First, the scale accuracy of these maps was checked. Using a micro-rule capable of accurately measuring 0.001 inch (2.5μ), map distances between various combinations of triangulation stations were measured. Next, the latitude and longitude coordinates of the triangulation stations were obtained as well as back azimuths and distances to other nearby triangulation stations (table 1). In order to check map scales, ground distances and azimuths between triangulation station pairs were calculated for maps T452 and T4520 with the use of a geodetic-inverse program. The geodetic-inverse program used was developed at the U.S. Geological Survey for use on a Hewlett-Packard model 9810A calculator and utilizes Robbin's formula (Bomford, 1962) for computation of azimuths and back azimuths between triangulation stations. The accuracy of this formula is very high for long distances, being $1x10^{-8}$at 1600 km. The error is greater for closer stations; however, it is still only 0.5 seconds at 30 m, well outside the limits of measurement on the 1:10,000 scale maps. The distance formula used computes meridian distance and a plane curve in the prime vertical, which are then used in conjunction with Legendre's Theorem to yield arc distance between two points. The ground distances obtained were then converted to scale distances and compared with the measured distances on the stable-base surveys. The mean ratio of distance calculated divided by distance measured yielded enlargement factors for the stable-base surveys.

A corroborative determination of enlargement factors was made by measuring map distances between United States Standard Datum projection lines on T452 and North American 1927 Datum projection lines on T4520 with the micro-rule and comparing these values with values of latitude and longitude intervals published for checking polyconic projections (U.S. Geol. Survey, 1964). The enlargement factor based upon the graticules was determined as the mean ratio of measured value to book value. The discrepancy between the two mean enlargement factors determined by measuring distances between (1) triangulation station paris, and (2) graticule pairs was only 0.001, well within accepted limits of accuracy determined by map line width. An average of the two mean ratios determined for each map was used for the final enlargement factor.

Table 1.--*COORDINATES AND AZIMUTHS FOR 1854 and 1929 TRIANGULATION STATIONS NEAR BOLINAS LAGOON, CALIFORNIA*

[[1]Sources: U.S. Government (1858) and U.S. Coast and Geodetic Survey (1949).]

STATION	LATITUDE	LONGITUDE	AZIMUTH	BACK AZIMUTH	TO STATION:	DISTANCE (meters)
Bolinas Coast Guard Mast	37° 54' 21.904"	122° 40' 58.324"	268° 36' 37.6"	88° 38' 58.5"	Ridge, 1929	5601.5
			298° 27' 05.4"	118° 29' 09.8"	Rocky Point, 1929	5629.2
			50° 03' 14.2"	230° 02' 35.1"	Ledge, 1929	2033.2
Dune, 1929	37° 54' 23.088"	122° 39' 45.217"	268° 31' 24.7"	88° 33' 00.7"	Ridge, 1929	3815.2
			310° 41' 16.1"	130° 42' 35.6"	Rocky Point, 1929	4171.0
			68° 08' 52.5"	248° 07' 28.5"	Ledge, 1929	3604.0
Ledge, 1929	37° 53' 39.556"	122° 42' 02.121"	258° 36' 19.6"	78° 39' 19.6"	Ridge, 1929	7302.3
Ridge, 1929	37° 54' 26.247"	122° 37' 09.097"	228° 16' 10.7"	48° 17' 02.9"	Mt. Tamalpais, 1929	2785.7
Rocky Point, 1929	37° 52' 54.871"	122° 37' 35.796"	101° 58' 32.4"	281° 55' 48.9"	Ledge, 1929	6652.0
			193° 02' 07.8"	13° 02' 24.3"	Ridge, 1929	2891.8
			227° 38' 44.0"	47° 39' 04.8"	Stinson, 1929	1117.4
Stinson, 1929	37° 53' 19.287"	122° 37' 02.003"	94° 53' 47.1"	274° 50' 42.8"	Ledge, 1929	7359.8
			175° 12' 06.9"	355° 12' 02.6"	Ridge, 1929	2071.7
Stinson Beach, Chimney, 1929	37° 53' 59.61"	122° 38' 43.54"	320° 19' 28"	140° 20' 10"	Rocky Point, 1929	2593.1
			82° 45' 13"	262° 43' 12"	Ledge, 1929	4891.0
Bald Hill, 1854	37° 53' 49.74"	122° 35' 19.84"				
Ballenas Bluff, 1854	37° 54' 08.55"	122° 40' 23.38"	292° 51' 19"	112° 53' 58"	Rocky Point, 1854	6845.2
Briones, 1854	37° 55' 17.76"	122° 41' 35.29"				
Embarcadero, 1854	37° 56' 04.59"	122° 40' 21.39"	51° 20' 28"	231° 19' 40"	Briones, 1854	2310.9
Embarcadero House, South Gable End, 1854	37° 55' 56.04"	122° 40' 54.42"	251° 54' 30"	71° 54' 51"	Embarcadero, 1854	848.5
Rodea Stake, 1854	37° 54' 08.27"	122° 40' 54.62"	192° 44' 59"	12° 45' 19"	Embarcadero, 1854	3676.8
			155° 07' 54"	335° 07' 29"	Briones, 1854	2361.2
Rocky Point, 1854	37° 52' 42.23"	122° 36' 05.24"	208° 02' 59"	28° 03' 27"	Bald Hill, 1854	2358.5

The U.S. Geological Survey topographic map of the 7-1/2′ Bolinas quadrangle, the modern base used in this study, published at 1:24,000, was enlarged to 1:10,000 scale on a stable base, and the accuracy of the enlargement was checked by the method just described. The surveys T452 (1854) and T4520 (1929) were photographically enlarged to a scale of precisely 1:10,000 to match that of the modern base. Negatives were then made of the accurately scaled 1:10,000 surveys and base map.

Not all triangulation stations used for the 1854 and 1929 surveys are printed on the modern base. Some stations were abandoned whereas others were lost or unrecoverable. Ballenas Reef Point station, for example, was in 1854 located on the cliffs above Duxbury Reef, an area that wave attack had eroded away by 1929. The Ballenas Beach station once located on Bolinas spit was washed away between 1854 and 1929. Station Ledge was physically moved and resurveyed. One station, Rocky Point, is shown on both T452 and T4520, but its utility for registration is diminished because its original location was mislocated by approximately 50 m (Swainson, 1929). The station was reestablished in 1929 to correct the original error, but by 1952 was lost, the pyramidal rock on which it was fixed having been blasted away (U.S. Coast and Geod. Survey, 1963). The station was subsequently established as "Rocky Point 2."

In order to use the old triangulation stations for registration, their positions were measured on the modern base from the U.S. Geological Survey graticules with the micro-rule and inked. Next, the United States Standard Datum graticule was measured and inked on the modern base. Positives of the 1854 and 1929 surveys and the modern base were then registered by alining triangulation stations and the U.S. Standard Datum graticules. Each positive was then registered to its corresponding negative. The negatives were then used in photographically compositing (1) the 1854 survey with the modern base, (2) the 1929 survey with the modern base, and (3) the 1854 survey with the 1929 survey. The stable-base copy of T452 obtained from U.S. Coast and Geodetic Survey archives was photographed from the original survey, which had been folded and torn. Portions of the original survey along the fold are missing (pl. 2); and in order to fill in missing linework, especially in the channels north of McKennan Island, reference was made to 19th- and early 20th-century U.S. Coast and Geodetic Survey charts of the San Francisco Entrance (for example, fig. 7). These charts were originally made from T452 and are now the best source for the missing linework. For each of the composited plates, the modern base was screened 50 percent to produce contrasting line weights with the survey linework.

After registration, each of the maps used in compositing the plates was cropped to include the immediate area surrounding Bolinas Lagoon. Figure 6 shows the original area encompassed by (1) the 1854 survey T452, and (2) the 1929 survey T4520.

Accuracy of registration of topographic surveys with modern base map

Registration of T4520, the 1929 survey by U.S. Coast and Geodetic Survey with the modern base (pl. 3), is good; and shorelines, cultural features and triangulation stations coincide. On plates 2 and 4, the 1854 survey appears to be shifted approximately 55 m northwest. This moves its position northwest with respect to T4520 and conclusions regarding quantitative changes in marsh areas, channels and other features must allow for this discrepancy. The misregistration may result from (1) misplaced projection lines, (2) erroneous triangulation station coordinates, or (3) unknown changes in locations of triangulation stations. Apparently this cannot be corrected by calculati@L&K&_A 930+Spartina optimal fit with existing topography could only be done by visually fitting T452 with the modern base, or by superimposing graticules added to the 1854 survey with those on the modern base.

This indicates that composites of old and new surveys may in some cases at best be approximately fitted. Problems in horizontal control were also encountered by Nichols and Wright (1971) in their study of historic margins of marshland in San Francisco Bay. They noted that in some places their control points were askew and "arbitrary decisions, based upon interpretations of local morphology, were made on how the data were to be adjusted. Compilations made by others would very likely differ in these areas." For purposes of their study, this was perhaps the best solution to the problem of misregistration.

This is an illustration of the philosophical dilemma of whether it is better to be vaguely right or precisely wrong. In the present study, the latter course was chosen because it is felt that the precision of registration is as important here as the accuracy of the fit. Because of the careful calculations used in obtaining the present registration of T452 to the modern base, it would be difficult to improve the precision, whereas merely by moving the 1854 survey (pl. 2) over either the 1929 survey (pl. 3) or the modern base on a light table, the accuracy of the registration may be instantly improved. In this study, the misregistration of T452 does not materially affect delineation of the 1906 fault trace on Pepper (Kent) Island or conclusions regarding changes in the lagoon from 1854 onward. The misregistration of T452 despite careful horizontal control is interesting in itself as an illustration of the problems encountered in registering 19th-century surveys to modern bases.

COMPARISON OF 1854/1929 U.S.C. & G.S. TOPOGRAPHIC SURVEYS OF BOLINAS LAGOON WITH REFERENCE TO THE 1906 EARTHQUAKE

The composited 1854 and 1929 surveys (pl. 4) reveal significant morphological changes in Bolinas Lagoon over a 75-year period. Many of the changes are very likely the result of cumulative effects of natural processes including erosion, sedimentation, marsh advance, deltaic progradation, and so forth. Human activity is also responsible for some of the observed changes. The most dramatic changes, evident in the island marshes, are tectonically caused.

Because Bolinas Lagoon is situated over the San Andreas fault, the 1906 earthquake caused numerous topographical changes within the lagoon as well as in the immediately surrounding areas. These changes are of interest because the sedimentary history of the lagoon is inextricably intertwined with the tectonic history of the area. Movements along the San Andreas fault, especially vertical movements, affect the sedimentary and stratigraphic record of the lagoon back to its nascent state. Observation and analysis of surface phenomena associated with the 1906 earthquake yielded clues regarding subsurface structure of the lagoon.

After the 1906 earthquake, G. K. Gilbert studied its effects in the region from Bolinas Lagoon to Tomales Bay and described the fault trace and various types of ground failure (Gilbert, 1908). Evidence from Bolinas Lagoon and surrounding areas indicated subsidence of parts of the lagoon and spit east of the 1906 fault trace. There may also have been coeval uplift of areas west of the fault, although evidence for this was equivocal. Gilbert's observations lead to the hypothesis that Bolinas Lagoon overlies a graben in the San Andreas fault zone.

Marsh changes on Pepper and McKennan Islands as indications of subsidence

Subsidence was reflected in subsequent changes in salt marshes east of the 1906 fault trace on Pepper (Kent) and McKennan (Pickleweed) Islands. Gilbert (1908) described the trace of the fault and the occurrence of landslides at the point where the fault trace left the lagoon and moved onshore. On land the fault was relatively easy to follow because of the evident mole track and offset linear features. Within the lagoon, however, the fault trace was more subtle, owing to (1) the plastic nature of the sediments, (2) the obscuring effect of marsh plants, and (3) the erosional effects of tidal currents. The most revealing sign of the fault trace within the lagoon occurred on the Pepper Island salt marshes. Nearly 5 months after the earthquake, Dr. S. S. Southworth of Bolinas indicated to Gilbert botanical evidence of subsidence of portions of Bolinas Lagoon east of the fault. Gilbert enlisted the aid of Willis L. Jepson, a botanist, in examining these marshes. On Pepper Island, the fault trace was clearly indicated by sharply contrasting differences in the color of Salicornia (pickleweed) salt marshes on either side (fig. 10). East of the fault trace, lowered

Salicornia and other marsh plants were dull brown, whereas west of the

Figure 10. View toward northwest on Pepper (Kent) Island, Ca. 1907. Fault trace trends N. 34° W. between Professor Willis L. Jepson and the water-filled depression; and is indicated by the boundary between downdropped, unhealthy brown (light-colored) marsh on the right (east) and healthy green (dark) marsh at left (west).

fault, the marsh remained a healthy green. In Gilbert's words, "The contrast was so strong, that the eye could readily trace the line of the fault" (1908, p. 82). The pronounced brown east of the fault was due to necrosis of large numbers of Salicornia and other marsh plants including (1) Limonium californicum (sea lavender), (2) Grindelia Cuneifolia Nutt (marsh grindelia), (3) Mesembryanthemum aequilaterale Haworth (sea fig), (4) Distichlis spicata (L.) (salt grass), (5) Frankenia grandifolia Cham and Schlect (yerba rheuma), (6) Triglochin maritima L. (arrow grass), and (7) Jaumea carnosa Gray (fleshy jaumea) (Jepson, 1908). Small trees of the genus Populus were also dead east of the fault trace on Pepper Island (Jepson, 1908).

Analysis of salt-marsh seed-plant distributions along leveled transects in San Francisco Bay marshes by Atwater and Hedel (1976) indicates that high-marsh plant communities, of which the suite described by Jepson (1908) is typical, generally occur 0 to 15 cm above MHHW. Their work corroborates findings that elevation and salinity are the principal ecologic controls on the distribution of marsh plants. A series of seven measurements along the en echelon cracks that formed the fault trace on Pepper Island yielded a mean value of 30 cm of vertical offset (Gilbert, 1908). A second series of measurements indicated 35 cm of displacement (Gilbert, 1907). Assuming elevation ranges of high-marsh plants in Bolinas Lagoon similar to those in San Francisco

Bay, a 30-cm minimum downdrop of part of Pepper Island in 1906 would have lowered the marshes to a level 15 to 30 cm below MHHW. This effectively increased tidal residence time over the depth-sensitive high-marsh plants, resulting in slow necrosis.

High-marsh plants such as Salicornia typically lack air storage tissue that has developed, for example, in the low-marsh plant Spartina (cordgrass), and as a result they are unable to endure extended periods of submergence. High-marsh plants also suffer from extended submergence because of the loss of osmotic pressure. During submergence, water moves out of the plant cells into the surrounding seawater, which has a higher concentration of solutes, and this water loss eventually kills the cells (Teal and Teal, 1969) and leads to the observed marsh-plant mortality.

1906 trace of San Andreas Fault within Bolinas Lagoon

A composite of surveys T452 and T4520 (pl. 4) can be used to relocate the 1906 trace of the San Andreas fault as well as to show cumulative changes in lagoonal morphology over the 1854-1929 period.

The extensive marshes shown on Pepper Island in the 1854 survey were greatly reduced by 1929. The only Pepper Island marshes indicated on the 1929 survey are (1) an elongate strip near the west side of the lagoon, and (2) a small area approximately 150 m long north of the tip of the spit. The combined area of these two marshes is only about one-third of the 1854 marsh area. Reduction of total marsh area apparently resulted primarily from deleterious effects of the 30 cm downdrop east of the 1906 fault trace. The unhealthy and dying marshes on Pepper Island described by Gilbert (1908) were subsequently completely destroyed, as seen on the 1929 survey. From this, it can be inferred the the 1906 trace lies at approximately the line of overlap of the Pepper Island marshes shown on the composite of the 1854 and 1929 surveys (pl. 4). The fault trace is also approximately defined by a major channel that formed through Pepper Island between 1906 and 1929. This channel is seen immediately east of the larger Pepper Island marsh on the 1929 survey (pl. 3). The inferred line of the 1906 trace is drawn on plates 1 and 5 along the marsh boundary and parallel to the channel trending N.34^{o}W., the direction of a 1907 sighting on the fault trace on Pepper Island by Gilbert (1908).

The 1906 fault trace between Pepper Island and the northwest shore cannot be located accurately because there are no offset features either on the ground or shown on the 1854 and 1929 composite (pl. 4) that can be used to establish its position. Gilbert (1908) inferred that the fault trace crossed Pine Gulch Creek delta "between the lines of high and low tide," but he could not be sure because he did not examine that area until after deposits from the floods of March 1907 obscured the fault trace. Northward projection of the N.34^{o}W. trend of the fault trace on Pepper Island results in placement of the fault too far east, at the head of the lagoon. Gilbert (1908, p. 67) recognized that the fault was either offset, or curved westward between Pepper Island and the northwest shore.

Horizontal displacement along the 1906 fault trace on Pepper Island

Horizontal fault displacement on Pepper Island was indicated by (1) offsets along the south shore, (2) the extent of marsh plants on the north part of the island, and (3) dead and dying marshes offset from healthy ones (Gilbert, 1908). These changes were observed 5 to 12 months after the earthquake and were then too indefinite to use for accurate measurement. In his field notes, Gilbert (1906) wrote: "At junctions of floras and at water edges the horizontal throw can be seen, but not measured -- 10-15 [ft]." Gilbert (1908) inferred that the horizontal displacement on the island was greater than the displacement at the nearest measured point on land, located about 1.5 km northwest of the lagoon. Here, just outside the boundary of plate 5, a line of eucalyptus trees was offset 3 to 4 m during the 1906 earthquake (Gilbert, 1908).

Fault-related features north of Bolinas Lagoon

The fault-related features north of the lagoon shown on plate 5 were discerned by ground observation and analysis of aerial photographs (series MRN 74, 7-27-65). The most prominent observable features consist of northwest-trending ridges bounded by generally steep scarps and troughs that include wet depressions and sag ponds. The linear features are discontinuous in places and form bifurcating patterns around the elongate ridges, resulting in large lens-shaped slivers in the San Andreas fault zone immediately northwest of the lagoon.

The description of the 1906 fault trace north of the lagoon by Gilbert (1908) follows the lineations plotted on plate 5. Near the point where the fault intersects the shore of the lagoon, several landslides obstructed the road following the earthquake (Gilbert, 1908). Just north of the landslides debris, the fault trace was followed and described by Gilbert (1908) as follows:

> ". . . beyond . . . the landslides the trace consists of a number of subparallel cracks occupying a belt several yards in width. There is also a nearly parallel branch of the trace in a fault-sag lying a little farther west, but this could be followed only a short distance . . . Mr. Nunes, who cultivated this sag, states that it once contained a pond or marsh, and this he had drained, but the water stood there again after the earthquake, showing that the earthquake had caused a depression of the bottom of the sag. The diffused cracks on the main line soon gather into a narrow belt and descend into a narrow sag, containing the barn and other farm buildings of the Steele place. After following the sag for a short distance, the trace generally rises on its

eastern wall, crosses obliquely an intervening ridge and enters a parallel sag toward the east. In this sag, which also is narrow, the trace intersects one of the roads leading from Bolinas to Woodville and immediately begins to ascend the narrow ridge bounding the sag on the east."

A map by Brown and Wolfe (1972) showing recently active breaks along the San Andreas fault between Bolinas Bay and Point Delgada indicates in a more generalized way topographic evidence of faulting in the area immediately north of the lagoon. Herd, Helley, and Rogers (1977) also plotted fault-related features in the vicinity of Bolinas Lagoon, although some of their interpretations differ from those shown on plate 5 in this report.

McKennan Island

McKennan (Pickleweed) Island lies entirely east of the 1906 fault trace, and the marshes there also deteriorated after the earthquake. A broad, sharply defined zone of dead and dying Salicornia marsh surrounded the island in the spring of 1907 (Jepson, 1908). A single measurement indicated at least 25 cm of subsidence; although it was noted that if lag time in plant response to extended submergence were taken into account, the amount of displacement could have been "several inches more" (Gilbert, 1908). Subsidence of McKennan Island was corroborated by a local resident who reported that after the earthquake he could sail over part of the island previously unnavigable (Gilbert, 1908).

Plate 4 shows a reduction of approximately 60 percent of the McKennan Island marshes between 1854 and 1929, probably mostly due to subsidence during the 1906 earthquake.

East shore of the lagoon

There was no clear-cut evidence for subsidence of the east shore of the lagoon. Jepson (1908) found little evidence of deterioration in the discontinuous marshes along the 5.5-km-long eastern edge of the lagoon. Gilbert (1908) found equivocal evidence of downdrop, noting that some marshes on the east shore appeared entirely healthy, whereas low-lying parts of other marshes exhibited deterioration. Other evidence of subsidence on the east shore was also contradictory. For example, the road along the east shore in places followed the strand between high and low water, and wagons forded water when crossing at high tide. After the earthquake, these fords apparently deepened and had to be crossed at lower tide levels. However, an east-shore resident, who daily crossed the lagoon by boat, noticed no change in bathymetry along his water front (Gilbert 1908). Because the east boundary fault of the Bolinas Graben apparently lies within the lagoon (pl. 5), evidence of subsidence along the east shore may be related more to liquefaction or slumping than to tectonic subsidence.

Plate 4 indicates reduction of marsh area along the eastern shore in the 1854-1929 period. Records of marsh deterioration resulting from the 1906 earthquake indicate that only a small part of marsh reduction along the east shore in the 1854-1929 period was earthquake related. Much of the marsh loss appears to be from fill for road construction and other purposes. The east-shore marshes generally occur near stream deltas, and from 1854 to 1929, the marshes in several places (pl. 4) advanced toward the lagoon. This suggests progradation of the stream deltas, which may be due in part to man's increasing activity in the watershed during the 1854-1929 period.

Marshes on Pine Gulch Creek delta

The progradation of Pine Gulch Creek delta from 1854 to 1929 (pl. 4) apparently provided areas of sufficient elevation to permit establishment of depth-sensitive salt marshes. From 1854 to 1929, the marshes on the west side of the lagoon, including the Pine Gulch Creek delta marshes, advanced as much as 200 m into the lagoon. During the same period, landward areas of this marsh were reduced along a zone 1 km long 50 to 250 m wide (pl. 4). The marsh reduction may have resulted from several causes including: (1) progradation of Pine Gulch Creek delta, (2) increased sedimentation due to plowing of fields immediately west of the marshes, and (3) road construction through the marsh prior to 1903 (U.S. Coast and Geod. Survey, 1903). It is also possible that the marshes were uplifted during the 1906 earthquake, although this is not documented. Gilbert (1908) described inconclusive evidence which suggests that some areas west of the fault were in fact uplifted. Barnacle mortality on pilings in the Bolinas waterfront indicated the possibility of a maximum of 15 to 20 cm uplift there (Kofoid, 1908). Local residents reported shoaling of the channel between Pepper Island and the distal end of the spit (Gilbert, 1908). However, channel shoaling does not necessarily imply uplift, because it may have resulted from liquefaction and lateral shifting of unconsolidated, water-saturated sediments.

A wave-cut platform or clam patch located about 1 km west of the channel entrance to the lagoon was accessible for clamming about 4 low tides per month prior to the earthquake, but accessible during about 20 low tides per month afterward (Gilbert, 1908). The inferred uplift of the clam patch was 30-35 cm.

To determine whether land west of Bolinas had been uplifted, Gilbert examined marshes in Limantour Bay for new Salicornia growth around raised salt-marsh regions. Gilbert did find new marsh growth in June 1907, extending 33 to 40 cm below former marsh edges (Gilbert, 1908). The new marsh growth seemed to confirm other evidence for uplift west of Bolinas (not west of the fault trace, because there was no evidence of uplift on Pepper Island). However, several months later, it was reported that the clam patch was again accessible only a few days per month. To check this subsidence, Gilbert returned to Limantour Bay where he found the new Salicornia growth had deteriorated in a 25-cm vertical zone (Gilbert, 1908). It appeared there had been rapid uplift during the 1906 earthquake, and subsequent subsidence of land west of Bolinas. The problems of conflicting evidence for uplift were never satisfactorily resolved, and whether there was uplift of broad areas of land is not known.

Marshes at the north end of Bolinas Lagoon

Comparison of surveys T452 and T4520 indicates that the marsh at the north end of the lagoon was eliminated between 1854 and 1929 (pl. 4). Marsh loss there appears to be largely caused by man. By 1903, approximately 200 m of roads had been built through the marsh (U.S. Coast and Geod. Survey, 1903). Deposits from Wilkins Gulch Creek, which flows into the lagoon about 100 m south of the apex of the lagoon, have also contributed to marsh destruction. An area east of Highway 1 that was marsh in 1854 is today covered by angular to subrounded, poorly sorted clastic debris, most of which appears to be stream deposited. Debris from a road cut near the foot of the ridge northeast of the former marsh may also have partially filled the marsh.

Marsh reduction at the apex of the lagoon also resulted from the 1906 earthquake. Gilbert (1908) noted that low-lying parts of the Salicornia marsh deteriorated in an irregular pattern after the earthquake. He described series of anastomosing surficial cracks in the marsh there, as well as in the marshes on Pine Gulch Creek delta. Surficial cracks formed in other marshes near the fault trace too, although not as distinctly. Individual cracks were approximately 2 to 8 cm wide, and showed no evidence of vertical or lateral displacement. Larger secondary cracks formed in a marsh north of Pine Gulch Creek (fig. 11). The cracks may have resulted from liquefaction and lateral movement of sediment during the 1906 earthquake. Liquefaction may also explain the irregular pattern of marsh destruction, which may result from uneven lateral flow of liquefied sediments.

Spit marshes and morphology

Marsh areas north of the spit were destroyed after the 1906 earth quake by washover sands. Near the west end of the spit, the fault trace consisted of a series of enechelon cracks (pl. 5), and residents of the Dipsea Inn, then located near the center of the spit, reported that after the earthquake the spit east of the fault was more frequently overtopped by waves, indicating subsidence (Gilbert, 1908). Because sands had shifted in the area of the fault trace on the spit, reliable measurements of vertical displacement could not be made.

By 1929, marshes destroyed as a result of the 1906 earthquake were reestablished intermittently along the north side of the spit and were more extensive than those of 1854 (pl. 2 and 3). The 1929 marshes were positioned farther toward the lagoon than those of 1854 and reflect (1) widening of the lagoon side of the spit during the 1854-1929 period, and

Figure 11. S. S. Southworth contemplating secondary ground crack in marsh north of Pine Gulch Creek, ca. 1907. View looking north toward head of Bolinas Lagoon. Pilings from a lighter wharf (California State Historical Landmark 221) can be seen at the extreme left just above water.

(2) an apparent landward recession of the MHW line on the ocean side of the spit noted by Swainson (1929).

During the 1854-1929 period, the largest increases in spit width, up to 150 m, occurred near the middle of the spit in the place which is now occupied by man-made Seadrift Lagoon (pl. 3 and 4). The extreme southeast part of the spit, which in places was only 100 m wide in 1854, had doubled in width by 1929. Along a distance of approximately 1-km at the western end of the spit, the width decreased as much as 100-m from 1854 to 1929. The narrowing of the spit here appears to be related to a southern shift of part of the main tidal channel, but may also be due in part to spit subsidence during the 1906 earthquake.

Widening of the spit is probably due in part to the build-up of washover fans or storm deltas on the lagoon side after the 1906 earthquake. Subsidence of the spit east of the 1906 fault trace facilitated overwash. Prior to the earthquake, overwash occurred only during storms with high winds, but after the earthquake, overwash was frequent (Gilbert, 1908). The last overtopping of the spit occurred in 1913 (Thomas J. Barfield in Ritter, 1973).

Overwash generally results only from storm waves that overtop the storm beach ridge or dune field on a barrier. Water passing the highest point of a barrier has residual kinetic energy as well as potential energy resulting from its elevation above the water level of the lagoon and thus flows toward the lagoon (Pierce, 1970). As the water flows down the backshore, it transports sediments which are deposited at lower elevations as water velocity decreases. Formation of washover fans is favored by a gently sloping, broad backshore with extensive adjacent barrier flats, because (1) the water maintains a low velocity and therefore does not erode deeply and (2) the width of the barrier dissipates water energy by friction (Pierce, 1970). Deposition thus occurs on gently dipping, back-barrier slopes and on the adjacent tidal flats, and forms broad fans. As these deposits build up, they further decrease the slope of the back-barrier, facilitating further deposition. This process apparently occurred on Stinson Beach spit, especially after the 1906 earthquake, as evidenced by (1) the descriptions by Gilbert (1908) regarding more frequent overwash after the earthquake, and (2) the widening of the eastern two-thirds of the spit during the 1854-1929 period (pl. 4). Figures 27a and 28a show washover fans behind the spit in 1907.

The eastern two-thirds of the spit were largely bounded by tidal flats on the lagoon side in the 1854 survey, whereas the west third was bordered closely to the north by the main tidal channel (pl. 2). The elevation of the spit was apparently sufficient to prevent overwash west of the fault after the earthquake. However, part of the spit bordered by the main channel on the lagoon side may have been overtopped. Where the spit is bordered by the channel, the back-barrier slope steepens at the channel edge. When water from overtopping waves reaches this point, its velocity is increased, enabling increased sediment transport. Most of this sediment is deposited in subtidal lagoon water and hence does not build up the back-barrier. Because of this, water from succeeding waves attains greater velocities, and the slope is increased because of erosion (Pierce, 1970).

Erosion of back-barrier areas that adjoin channels can thus occur from overtopping waves and may account for narrowing of this part of the spit. It cannot be established that this occurred, but it is one possible mechanism that explains narrowing of the west part of the spit and simultaneous widening of the remainder in the 1854-1929 period (pl. 4).

West end of spit

Changes in MHW line in the western 200 m or so of the spit from 1854 to 1929 are not especially significant because the configuration above MHW in this area changes markedly depending upon year, season, and tide levels. Figure 12 shows a series of superimposed outlines of the distal end of the spit to illustrate the variablility of morphology there. The outlines are taken from various aerial photographs and thus cannot be directly compared with the surveyed MHW lines on the 1854 and 1929 U.S. Coast and Geodetic Surveys.

Swainson (1929) noted that the inlet widened about 40 m in the 1854-1929 period, but his is also not significant because inlet width is largely controlled by configuration of the distal end of the spit. Widening of the west side of the inlet is restricted by the cliffs; but the east side which is composed of unconsolidated sand and gravel fluctuates laterally. Measurements along the ocean side of the west end of the spit indicated about 49 m of northeast movement of the high-water line between January and August 1968, and a 90 m widening of the inlet between August 1967 and December 1968 (Ritter, 1973). Because short-term fluctuations of inlet width exceed the change from 1854 to 1929, the long-term change is not significant in terms of lagoonal sedimentary history.

Outer MHW line on Stinson Beach spit

Changes in the position of the MHW line on the ocean side of Stinson Beach spit indicated on the 1854 and 1929 surveys may not show the actual magnitude of shoreline recession, because the MHW line shifts according to season. The report accompanying the 1929 survey indicates slight spit recession during the 1854-1929 period (Swainson, 1929), but gives no quantitative measure. Small shifts of the MHW line are generally insignificant because the amount of change is within the limits of (1) the seasonal range of MHW shifts, and (2) drafting and survey accuracy (Interstate Electronics Corp., 1968).

Data from surveys of the MHW line on the ocean side of Stinson Beach spit from 1948 to 1970 were plotted by Johnson (1971) and are

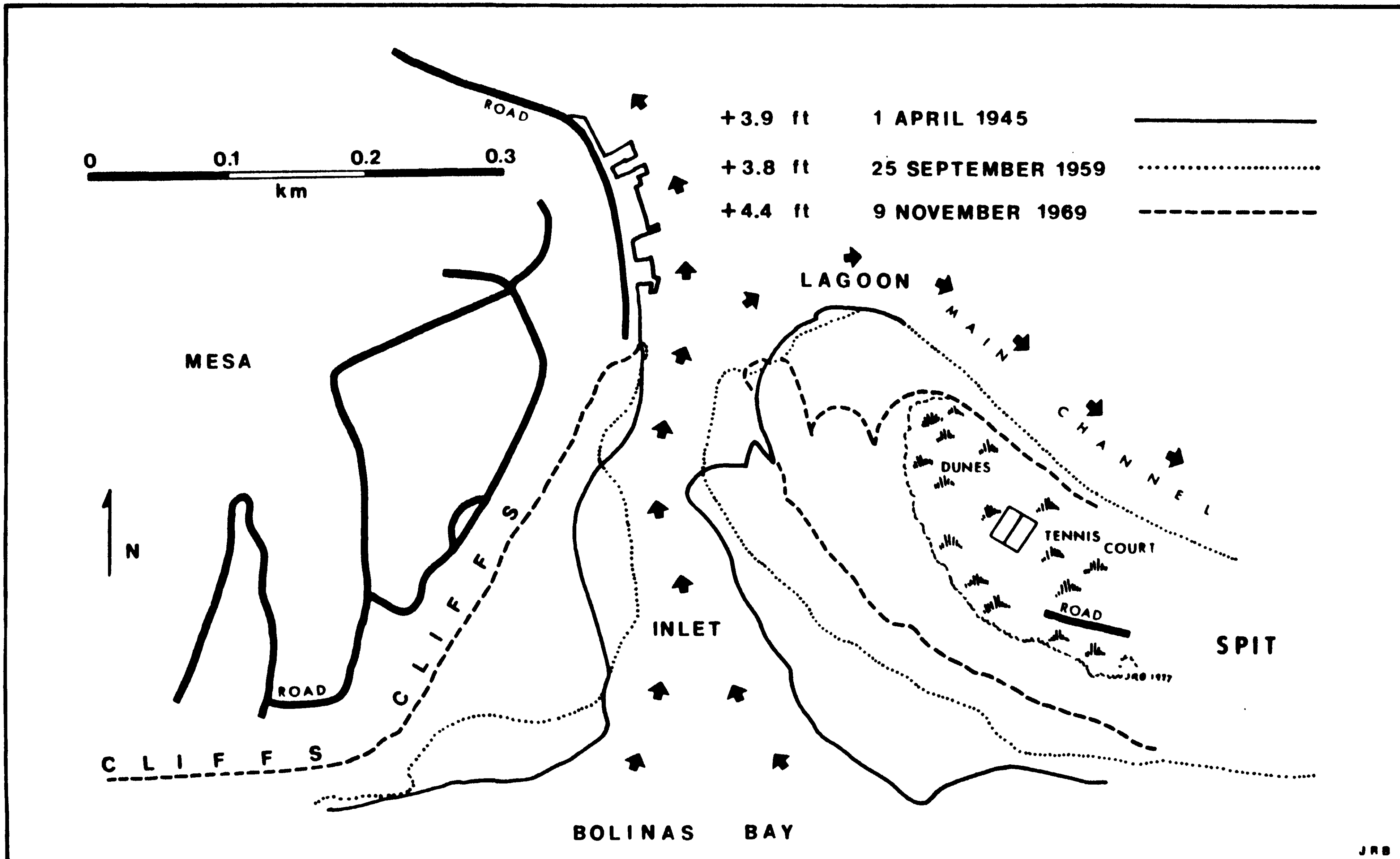

Figure 12. Map showing variable configuration of inlet and distal end of Stinson Beach spit. Linework taken from aerial photographs in Johnson (1973).

shown in figure 13. Distance of the MHW line from reference points on land were plotted against time of year. The resulting graph indicates that the position of the summer MHW line on the spit may be shifted over 45 m southward from the winter MHW line.

Beach profiles, and corresponding MHW lines, are closely related to wave steepness, which is the ratio of wave height to wave length (Johnson, 1971). During periods of low wave steepness, beaches build low berms with associated steep beach-face profiles; during periods of high-wave steepness (storm conditions), beaches become less steep (Johnson, 1971). In Bolinas Bay, wave steepness is greatest during winter and early spring and corresponds to recession of the MHW line. Because the MHW line on the ocean side of the spit is a fluctuating line, its position on a survey fails to indicate its dynamic character.

The best quantitative measure of spit recession may come from analysis of recession of the Bolinas Cliffs west of the inlet. Stinson Beach spit is in a state of dynamic equilibrium, although the exact nature of the controls is not fully understood (Interstate Electronics Corp., 1968). A major factor controlling the position of the spit is the position of the Bolinas Cliffs that extend from the inlet to Duxbury Reef. As the cliffs recede because of wave attack, the equilibrium conditions of the spit are altered, and spit recession ensues as equilibrium is reestablished. In short, cliff recession causes consequent spit recession.

Erosion of Bolinas cliffs

The cliffs between the inlet and Duxbury Point (fig. 14) eroded approximately 30 m during the 1854-1929 period (Swainson, 1929). This figure may thus represent the distance of spit recession during that period as well, assuming the maintenance of the approximate logarithmic-spiral shoreline configuration (Yasso, 1965) from Duxbury Reef to Rocky Point.

A more recent rate of cliff erosion of 0.45 m/yr between the inlet and Duxbury Point was calculated by Alan J. Galloway (in Ritter, 1973) and is only slightly higher than the 0.40 m/yr average for the 1854-1929 period.

Other measurements of cliff retreat west of Bolinas from 1854 to 1929 (fig. 14) are: (1) 50 m at Bolinas Point, (2) 40 m 1 km north of Bolinas Point, (3) 70 m in the bight between Bolinas Point and Duxbury Point (part of which may be due to errors on T452), and (4) 60 m at Duxbury Point (Swainson, 1929).

Examination of aerial photographs indicates that erosion of the cliffs west of the inlet provides one source of sediment that is deposited in the lagoon. Most of the suspended sediment along the shore near the cliffs comes from the Monterey Shale, and assuming an erosion rate of 0.45 m/yr, approximately 28,000 m^3 of sediment per year are carried away by ocean currents (Ritter, 1973).

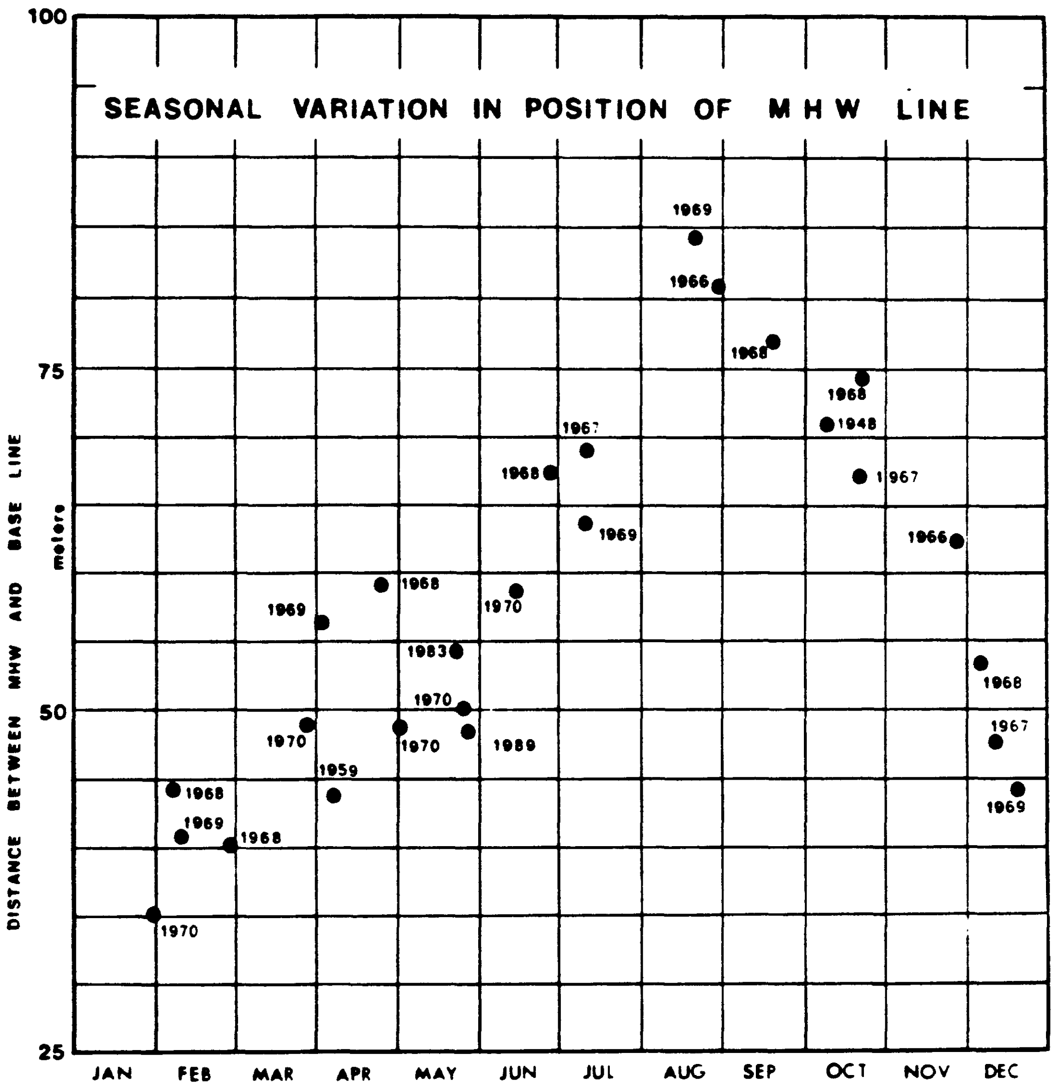

Figure 13. Seasonal variation of the mean high water (MHW) line on the ocean side of Stinson Beach spit relative to fixed reference points, 1948-1970. Figure modified after Johnson (1971).

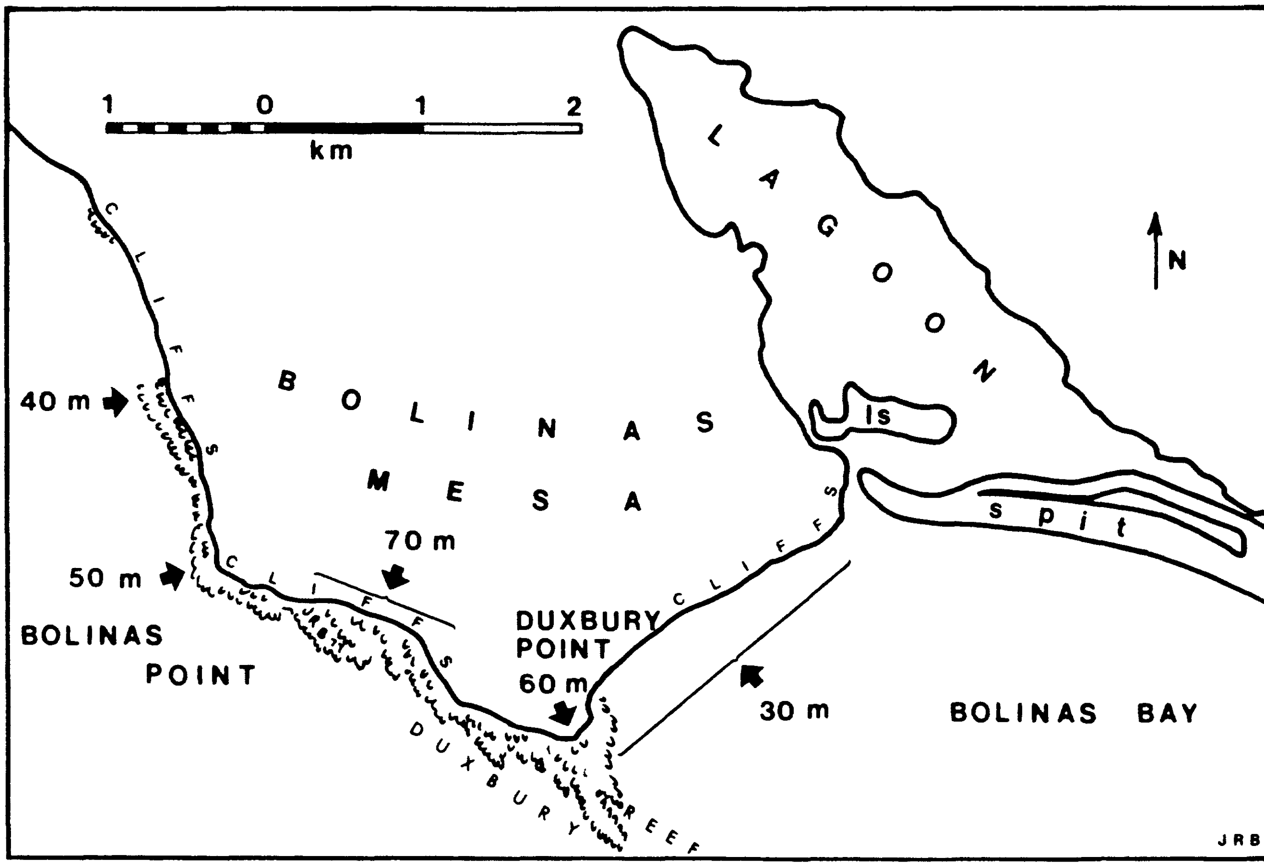

Figure 14. Map of Bolinas Lagoon and outer coast showing net cliff recession during the period 1854-1929. The 70 m figure for the bight between Bolinas and Duxbury Points may be excessive because of error in the original survey. Measurements from Swainson (1929).

Channels

Changes in the larger channels in the lagoon from 1854 to 1929 are shown on plate 4. In addition to the slight southward migration of the main tidal channel near the distal end of the spit, discussed above, examination of plate 4 reveals several other significant differences in channel positions.

The tributary channel immediately north of the central point of the spit in 1854 was eliminated by 1929. The reason for this may be inundation by washover after the 1906 earthquake.

From 1854 to 1929 the main channel migrated approximately 200 m southeast near McKennan Island, causing erosion of as much as 100 m of the northwest side of the island.

The north-south channel across Pepper Island shown on the 1929 survey is not evident on the 1854 survey, even in rudimentary condition. It is thought that this channel developed after 1906, in the sheared sediments along the fault trace. Aerial photographs show that this channel progressively narrowed after 1939, and by 1967 was almost completely filled with sediment (Gilroy, 1970). Figure 15 shows the changes in this channel since 1929. Today the Kent Island channel is almost completely filled and overgrown with high-marsh plants.

Progradation of Pine Gulch Creek delta from 1854 to 1929 eliminated the small channel shown on the west side of the lagoon on the 1854 survey. Much of this deltaic growth came after the 1906 earthquake. Extensive ground failure in the watershed facilitated erosion, and floods in the spring of 1907 apparently deposited large volumes of sediments in the delta.

Summary

Comparison of the composited 1854 and 1929 surveys indicates significant changes in lagoonal morphology as well as an accurate location of the 1906 trace of the San Andreas fault as determined by (1) changes in salt-marsh configurations, (2) the position of Kent Island channel, and (3) azimuths recorded by Gilbert (1908).

Observed morphologic changes include (1) extensive decrease in marshes on Pepper (Kent) Island, McKennan (Pickleweed) Island, and the lagoon side of the spit, due largely to subsidence during the 1906 earthquake, (2) minor decreases in marshes at the apex of the lagoon and along the eastern shore, due in part to the 1906 earthquake, (4) cliff recession between the inlet and Duxbury Point, (5) recession of the MHW line on the ocean side of the spit, probably related to cliff recession west of the inlet, and (6) southeast migration of the main channel near McKennan Island.

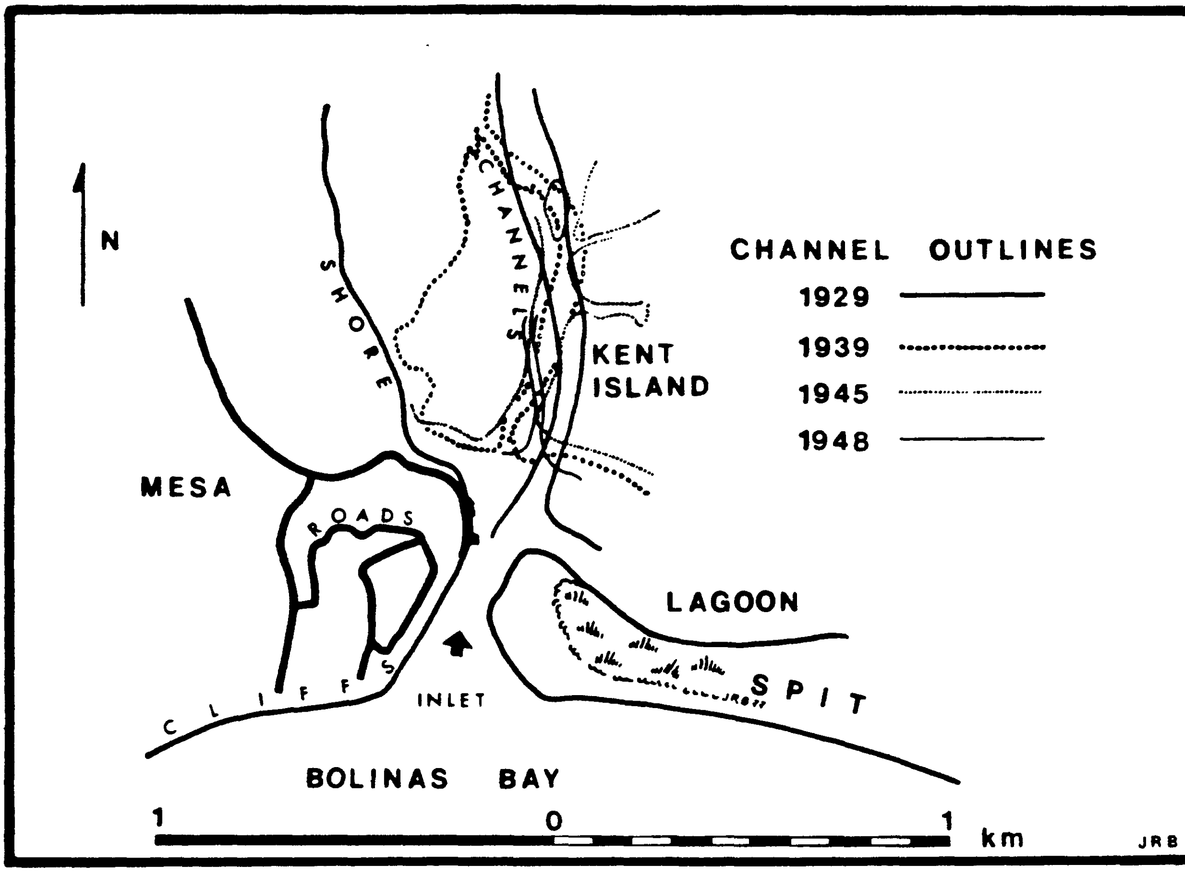

Figure 15. Map showing progressive shifting and narrowing of Kent Island channel 1929-1948. The 1906 earthquake downdropped the island east of the fault trace 30 cm, and the channel originally developed along the line of displacement. By the early 1960's this channel was almost completely filled with sediment. Linework taken from aerial photographs in Gilroy (1970), and from U.S. Coast and Geodetic topographic survey T4520.

SUBSURFACE STRUCTURE OF BOLINAS LAGOON

Tectonic, seismic, and topographic evidence strongly suggested the presence of a graben beneath Bolinas Lagoon, and seismic profiling was recently done to verify its existence and to determine its limits. Previous evidence of a graben included (1) subsidence of part of the lagoon east of the San Andreas fault during the 1906 earthquake, (2) truncation of the interdrainage ridges east of the lagoon, (3) the horst and graben topography of the area between Bolinas Lagoon and Tomales Bay, and (4) identification of an offshore graben by Cooper (1973). Seismic profiling by the writer indicates the presence of a fault that parallels the east shore of the lagoon and that is very likely a graben boundary fault.

Subsidence during 1906 earthquake

Evidence discussed in detail above indicates 25-35 cm of subsidence in the lagoon east of the 1906 fault trace (Gilbert, 1906, 1907, 1908). On Pepper Island vertically offset Salicornia marshes along the fault trace indicated averages of 30 to 35 cm subsidence to the east, and no vertical movement of the island west of the fault (Gilbert, 1906, 1908). The single measurement on McKennan Island indicated subsidence of at least 25 cm (Gilbert, 1908). Increased post-earthquake overwash on Stinson Beach spit east of the fault trace indicated subsidence; and although the subsidence could not be measured, it was estimated to be as much as 60 cm (Gilbert, 1907). Evidence from marshes generally indicated no subsidence of the east shore of the lagoon (Gilbert, 1908; Jepson, 1908; Kofoid, 1908). Together, this evidence suggested that the boundary between the downdropped part of the lagoon and the stationary areas lies between McKennan Island and the east shore. Gilbert (1908) suggested that the limit of subsidence was:

> "an old line of dislocation which coincides approximately with the northeast side of the lagoon. This dislocation has not been determined by a study of the geologic structure, but is indicated by the physiography, and was presumably concerned in the making of the basin occupied by the lagoon."

There was no clear-cut evidence of subsidence in marshes at the apex of the lagoon, and on a stretch of level ground 1.5 km north of the lagoon there was evidence of no vertical offset (Gilbert, 1908).

Pepper and McKennan Islands are approximately 1 km apart, and using values of 30 and 25 cm subsidence respectively, the slope of the graben is less than $0^{o}2'$w, indicating nearly level downdrop along this east-west line. Evidence of no vertical offset north of the lagoon, 25-30 cm on the island, and as much as 60 cm on the spit indicates (1) that the graben was hinged on the north, or (2) that the graben is broken by E-W trending faults along which there was differential vertical movement during the 1906 earthquake.

Explanation of numbers on plate 2,
1854 survey[1] superimposed on modern base[2]

1. MHW line. Delineates land/water boundary. Horizontally accurate within 10 m at rod stations (Shalowitz, 1964).

2. Inner edge of marsh. Delineates marsh/upland boundary. Does not define a tidal plane and may be approximately located (Shalowitz, 1964).

3. Outer edge of marsh. Not necessarily coincident with MHW line (Shalowitz, 1964).

4. MLLW line. Approximately located, and does not define a tidal plane (Shalowitz, 1964).

5. Approximate drainage pattern.

6. McKennan (Pickleweed) Island.

7. Pine Gulch Creek delta.

8. Pepper (Kent) Island.

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[1]U.S. Coast Survey topographic survey T452.
[2]Bolinas, Calif., 7 1/2′ quadrangle.

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Explanation of numbers on plate 3,
1929 survey[1] superimposed on modern base[2]

1. MHW line. Delineates land/water boundary. Horizontally accurate within 10 m at rod stations (Shalowitz, 1964).

2. Inner edge of marsh. Delineates marsh/upland boundary. Does not define a tidal plane and may be approximately located (Shalowitz, 1964).

3. Outer edge of marsh. Not necessarily coincident with MHW line (Shalowitz, 1964).

4. MLLW line. Approximately located and does not define a tidal plane (Shalowitz, 1964).

5. Kent Island channel. Formed after 1906 earthquake, parallel to fault trace. Persisted until mid-1960's.

6. McKennan (Pickleweed) Island.

7. Pine Gulch Creek delta.

8. Pepper (Kent) Island.

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[1]U.S. C. & G. S. topographic survey T4520.
[2]Bolinas, Calif., 7 1/2' quadrangle.

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Explanation of numbers on plate 4,
1854 survey[1] superimposed on 1929 survey[2]

1. Anastomosing surface cracks in marsh muds and partial destruction of Salicornia marsh caused by 1906 earthquake (Gilbert, 1908, p. 74, 83).

2. Sporadic destruction of some low-marsh areas caused by 1906 earthquake (Gilbert, 1908, p. 82, 83, 91).

3. Condition of marshes generally indicated no subsidence of east shore of lagoon due to 1906 earthquake (Gilbert, 1908, p. 91).

4. Lagoonward migration of marshes from 1854 to 1929. May be due to progradation of stream deltas and by road cut and fill.

5. Anastomosing surface cracks in marshes on Pine Gulch Creek delta caused by 1906 earthquake (Gilbert, 1908, p. 74).

6. Salicornia marshes remained healthy west of fault trace after 1906 earthquake indicating no subsidence (Gilbert, 1908, p. 66, 91).

7. 1906 fault trace parallels boundary between 1854 and 1929 marsh areas.

8. Average of 30 cm subsidence during 1906 earthquake caused destruction of depth-sensitive Salicornia marshes on Pepper (Kent) Island east of fault trace (Gilbert, 1908, p. 66, 82, 91).

9. Main tidal channel shifted southeast from 1854 to 1929. Southeast migration continues and is eroding northwest side of Pickleweed Island.

10. McKennan (Pickleweed) Island surrounded by zone of dead and dying Salicornia marsh after 1906 earthquake indicating subsidence of at least 25 cm, possibly several inches more (Gilbert, 1908, p. 82, 83, 91).

11. Large areas of marsh destroyed by washover sands as a result of subsidence of spit east of the 1906 fault trace (Gilbert, 1908, p. 82, 83).

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[1]U.S. Coast Survey topographic survey T452
[2]U.S. C. & G. S. topographic survey T4520

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Explanation of numbers on plate 5,
Tectonic and fault-related features[1]

1. Linear vegetation pattern.

2. Sag pond.

3. Northeast-facing scarp.

4. Northwest-trending scarp-bounded ridge.

5. Southwest-facing scarp.

6. Northwest-trending trough.

7. Sag depressions.

8. Northwest-trending ridge.

9. Elongate northwest-trending trough.

10. Northeast-facing scarp and northwest-trending trough.

11. 1906 fault trace swerves or is offset between Pepper (Kent) Island and northwest shore of Lagoon (Gilbert, 1908, p. 67).

12. Progradation of Pine Gulch Creek delta obscured 1906 fault trace by March, 1907 (Gilbert, 1908, p. 67).

13. North-trending series of disconnected (secondary) ground cracks after 1906 earthquake (Gilbert, 1908, p. 67).

14. En echelon cracks trending approximately north along 1906 fault trace (Gilbert, 1908, p. 66).

15. Inferred right-lateral offset greater than 4 m on Pepper (Kent) Island (Gilbert, 1908, p. 70, 71).

16. No evidence of uplift or subsidence of Pepper (Kent) Island west of 1906 fault trace (Gilbert, 1908, p. 83).

17. Average of 30 cm subsidence of Pepper (Kent) Island east of 1906 fault trace (Gilbert, 1908, p. 83).

18. 1906 fault trace trends N 34° W on Pepper (Kent) Island (Gilbert, 1908, p. 27).

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[1]Other interpretations of fault-related features appear on maps by Brown (1967, 1970), Brown and Wolfe (1972), Blake and others (1974), and Herd and others (1977).

19. Location of San Andreas fault determined from seismic profiles (J. R. Bergquist, unpub. data).

20. Shoaling of tidal channel between Pepper (Kent) Island and mainland caused by 1906 earthquake (Gilbert, 1908, p. 81).

21. 1854 outline of McKennan (Pickleweed) Island _Salicornia_ marshes.

22. Subsidence of at least 25 cm, possibly several inches more (Gilbert, 1908, p. 82, 83).

23. More frequent overwash east of fault trace after 1906 earthquake indicating probable subsidence of part of spit (Gilbert, 1908, p. 66).

24. Location of graben fault determined from seismic profiles (J. R. Bergquist, unpub. data).

25. Approximate trace of graben fault determined from high-resolution seismic profiles (A. Cooper, written commun., 1976).

26. Approximate trace of San Andreas fault determined from high-resolution seismic profiles (A. Cooper, written commun., 1976).

27. East boundary fault (Galloway, 1977; David L. Wagner, written commun., 1977).

28. San Andreas graben (Cooper, 1973).

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Truncated ridges east of Bolinas Lagoon

East of the lagoon, the toes of the southwest-trending interdrainage ridges are truncated along a line that parallels the shore of the lagoon. The abrupt steepening of the ridges suggests faulting because (1) the truncated toes also occur on ridges in the valley north of the lagoon, and (2) the geometry and continuouly shallow depth of the lagoon or embayment would tend to dissipate wave energy, resulting in low-amplitude waves with low erosional potential; hence the truncated ridges probably are not wholly wave cut. Presence of a bay mouth barrier or spit would further reduce the likelihood of wave-cutting.

Topography from Bolinas Lagoon to Tomales Bay

Along the San Andreas fault between Bolinas Lagoon and Tomales Bay, there is a zone up to 2 km wide characterized by northwest-trending ridges up to 5 km long bounded by parallel valleys and sags. Some of the ridges wedge out, and others are truncated and bounded by valleys in the same trend line (Gilbert, 1908). This topography, part of which is shown on plate 5, suggests a series of differentially downdropped slivers, or horst and graben structures, and the evidence of subsidence in the lagoon suggests that it may be underlain by similar structure.

Evidence of faulting on the Golden Gate platform

High resolution seismic reflection profiles across the Golden Gate platform indicate the presence of a 1- to 4-km-wide graben (fig. 16) that extends from Bolinas Bay to about 10 km south of the Golden Gate where its boundary faults become indistinct (Cooper, 1973). West of Rodeo Lagoon, reflectors dip into the west side of the graben at 11° and indicate approximately 20 m vertical displacement (cooper, 1973). The graben boundary faults are crossed by the main trace of the San Andreas fault (fig. 16), but near the north end of Bolinas Bay, the west boundary fault and the San Andreas appear to be coincident. Thus, assuming no offset, the 1906 fault trace across Pepper Island is probably the projection of the combined San Andreas/graben boundary fault. The east graben fault (pl. 1, 5) projects into the lagoon near the widest part of the man-made lagoon and along the east shore.

Seismic reflection profiling in Bolinas Lagoon

Seismic profiling was done in Bolinas Lagoon in order to: (1) determine the existence and location of the east boundary fault of a graben presumed to underlie the lagoon because of the several lines of evidence previously discussed, (2) determine thickness of the sediment prism and basement configuration, (3) determine the position of the San Andreas fault and vertical offset, and (4) correlate seismic reflectors with stratigraphy determined from boreholes drilled on Stinson Beach spit.

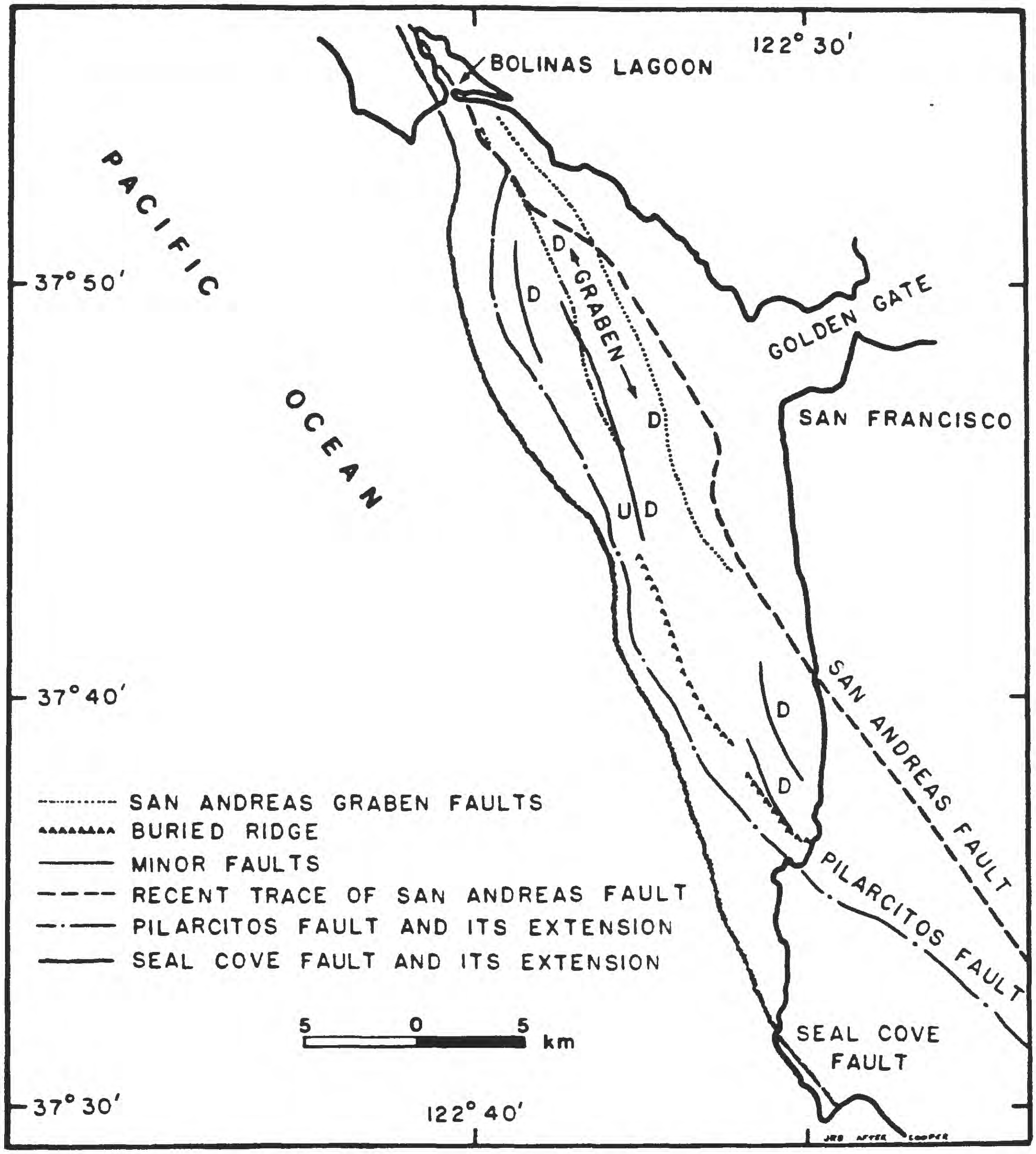

Figure 16. Map showing faults on the Golden Gate Platform determined by seismic profiling (Cooper, 1973) and their extensions on shore. Figure modified after Cooper (1973).

Rough seas prevented offshore profiling along lines orthogonal to the spit which may reveal (1) offshore structure, and (2) the degree of retention of transgressive marine and estuarine sediments.

Approximately 14 km (7.5 nautical miles) of seismic track line were run 24 November 1976 between 1000 and 1630 hours PST. High tide, corrected for Bolinas Lagoon from predicted values for San Francisco listed in Tide Tables (National Ocean Survey, 1976), was +4.5 ft. at 1321 hrs.

Field methods

The seismic reflection survey was made from a 5-meter, shallow-draft, flat-bottomed boat, and the equipment used included (1) EG&G dual uniboom transducer plates and catamaran, (2) EG&G high resolution hydrophone, (3) two EG&G Model 234 power sources, (4) EPC Model 4100 strip-chart recorder, and (5) a generator.

The dual uniboom consists of two sound source transducers incorporatd into a semifloating catamaran that was connected to the port side of the boat by a tow-line and to the power sources by electrical cables. A yoke was attached to the catamaran so that it could be kited in the desired track line outside the boat wake, away from propeller turbulence. A floating hydrophone was trailed from the starboard side and rigged from a gaff so it could be positioned with respect to the uniboom in order to record optimum signals. Cable from the hydrophone connected to the continuous-feed strip-chart recorder, which inscribed the reflected seismic signals.

A gasoline-powered generator supplied electricl power for the strip-chart recorder and the power sources. The power source, consisting essentially of capacitors and switches, alternately stored and discharged power to the dual uniboom. Power was first set at 200 joules, but later changed to 300 joules to improve quality of the seismic record. Sweep and firing rates were 0.25 sec.; and filter settings for the recorder ranged from 600 to 1600 Hz. The velocity of the uniboom-generated wave is 183 m per 0.25 second.

The boat was run at 2 to 4 knots during the seismic survey; faster speeds caused partial submergence of the uniboom. Resulting turbulence then caused air bubbles over the transducer plates impeding wave transmission and resulting in a greatly weakened signal and a poorer seismic record. Bearings on landmarks were taken at irregular intervals and subsequently used to position the track lines on a map (pl. 6).

Seismic record

Good seismic records were obtained for approximately 7.7 km (4.1 nm) of trackline, and records for 6.3 km (3.4 nm) of trackline in the north half of the lagoon are useful primarily for bathymetry and not for subbottom structure because faulty electrical grounding caused obscured records. In addition to velocity of the boat and faulty grounding, other factors that affected the quality of the record are (1) shallow water that caused multiples that partially or wholly obscured signals from subbottom reflectors, (2) varying absorptive characteristics of different sediment types, (3) distance between uniboom and hydrophone, and (4) vibrations from the generator and outboard motor.

Subsurface structure of Bolinas Lagoon was interpreted from the usable portion of the seismic record and is plotted on plate 7.

Seismic patterns interpreted as the San Andreas fault were found in the records of traverses south of Kent Island and are located approximately along the line of the 1906 trace determined from comparison of 1854 and 1929 U.S.C. & G.S. surveys (pl. 4). The amount of vertical offset is indeterminate, but downdropped to the east, and this is in agreement with postearthquake observations by Gilbert (1908). An indication of total offset across the San Andreas fault is the change in depth to acoustic basement on either side of the fault. Approximately 100 m west of the fault, south of Kent Island, acoustic basement is 21.5 m below the surface and just east of the fault, acoustic basement is 34 m below the surface. Part of the difference in depth to acoustic basement may be attributable to east-dipping reflectors.

Faults were also found on the east side of the lagoon, and one of these is thought to be the east boundary fault of the Bolinas Lagoon graben. This structure was encountered between points 13 and 11 (pl. 6, 7), and east of Pickleweed Island near point 8. The fault encountered at these places is inferred to be the same. Offset acoustic reflectors indicate downdrop of the west side with approximately 5 m offset at a depth of approximately 28 to 33 m. This fault does not have apparent surface expression, and appears to be overlain by a thin layer of nearly horizontal sediment. Slump structures apparently occur on the downthrown side at a depth slightly above the acoustic basement. Interestingly, this fault occurs near the projection of the offshore graben fault discovered by Cooper (1973) (fig. 16, pl. 5). Therefore, the southeast extension of the east boundary fault found in this study may connect with the offshore San Andreas graben fault found by Cooper (1973). The northeast extension of this fault, north of point 8 (pl. 6), is not definitely known, but is inferred to pass within the lagoon to a point east of the apex of the lagoon (pl. 1, 5) where it comes on shore. At this point the fault appears to be overlain by Quaternary terrace gravels. The fault north of this point is largely

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concealed by recent alluvium and landslides, but trends northwest to a point in the unnamed gulch between Copper mine and Wilkins gulches where Merced and Franciscan rocks are in fault contact (David Wagner, written Commun., 1977). Northwest of this gulch, the fault separates large blocks of Merced Formation and smaller slivers of Franciscan rocks from the main ridge of Franciscan rocks to the east (Galloway, 1977). About 2 km northwest of Woodville, the fault bifurcates with one branch largely separating Merced and Franciscan rocks, and the other cutting wholly through Franciscan rocks (David Wagner, written commun., 1977). Because the northwest extension of the east boundary fault found by seismic profiling largely separates Merced and Franciscan rocks, it is possible that much of the lagoon west of this fault is underlain by Merced formation. This inference was not verified by drilling on the spit, because bedrock was never reached in any of the boreholes. The acoustic basement of the seismic record appears to be a major change in sediment type, not bedrock, and therefore shows no indication that might signify a change in underlying bedrock across the east boundary fault. To summarize, there is no direct evidence for the bedrock type that occurs beneath the lagoon between the 1906 San Andreas fault trace and the east boundary fault. Immediately north of the lagoon, however, the area between these faults primarily includes Merced Formation. Therefore, there is a good possibility that Merced Formation also lies between these two faults beneath the sediments of Bolinas Lagoon (pl. 1).

The acoustic basement in part may represent the boundary between (1) overlying marine and estuarine sediments consisting of poorly consolidated sands, silty sands, and silts, and (2) underlying lacustrine peaty clay and clayey silt. The lower unit is thought to represent freshwater lake or pond desposits because of (1) fossil pollen content (discussed later), (2) abundant peaty organic remains, (3) the lack of marine or estuarine shells, and (4) similarity to sag pond deposits taken from the area north of Bolinas Lagoon for another study (Brian F. Atwater, oral commun., 1976). The sands and silty sands overlying the freshwater deposits are marine or estuarine as indicated by megafossils contained in them; and the contact between the two sedimentary units may be an unconformity.

The depth to this unconformity(?) in borehole 4 is 35 m, and generally corresponds to depths of acoustic basement in the central part of the lagoon. Depths in meters to acoustic basement along the track line are shown on plate 7. As the center of the lagoon is approached from either side, the depth to acoustic basement typically becomes deeper, with a maximum depth of approximately 39.5 m near the east side of Kent Island. Near this point is the apparent axis of a broad syncline. The depth to acoustic basement is apparently not systematic, because along the track line from points 14 to 8 (pl. 6), it alternately deepens and shallows. The deepest acoustic basement, 45 m, was found between points 11 and 9 (pl. 6); and between points 9 and 8 the acoustic basement was as deep as 41.5 m. The proximity of these two deep points indicates that they may be part of the same depression, although it would take additional profiling to determine this. This apparent depression may be related to a possible fault located along the track line near Pickleweed Island between points 9 and 8; however, there appears to be no surface expression of this fault.

The anticline and syncline detected along the track line from point 20 to 14 (pl. 6, 7) may be related to preexisting drainage topography on the eastern margin of the lagoon. The irregular nature of the acoustic basement from points 18 to 14 (pl. 6, 7) may be caused by (1) its shallow depth, or (2) real differences in the type of acoustic basement east of the graben fault.

DEPOSITIONAL HISTORY DETERMINED FROM DRILLING BENEATH STINSON BEACH SPIT

Analysis of borehole logs (fig. 19, PL. 8, 9, 10, 11) from Stinson Beach spit indicates that this area is underlain by complex discontinuous sequences of marine and estuarine sediments resulting from both vertical and lateral shifts of successive depositional environments.

These sediments include (1) marsh deposits, (2) dune sands, (3) spit or bay-mouth barrier deposits, (4) berm and washover sands and gravels, (5) channel and storm gravels, (6) beach sands, (7) tidal flat muds and sands, and (8) sublittoral silty sands. These sediments accumulated since 7770$\pm$65 yrs. B.P., the approximate date of the marine transgression. In part, these sediments overlie freshwater lake or pond sediments as determined from analysis of fossil pollen.

It cannot be determined whether the complete depositional record is present. Depending upon the balance between rates of sea-level rise and tectonic subsidence there may have been coastal erosion and consequent loss of part of the sedimentary record. The entire sequence of near-shore sediments is filling a drowned valley with relief exceeding 50 m.

Field methods

Boreholes were drilled beneath Stinson Beach spit to obtain information regarding the depositional and tectonic history of the area since the last major rise in sea level. The fieldwork was done during December 1975 and August 1976. Six boreholes were drilled (fig. 17), but BH-3 & 6 is a composite of two boreholes drilled on different dates at the same site, and the record from borehole 1 is intermittent and unreliable because of problems encountered in drilling with hollow stem auger. Borehole 4 was drilled within 10 m of BH-1. Boreholes 2, 4, and 5 were drilled east of the 1906 trace of the San Andreas fault, and borehole 3 & 6 was located west of the 1906 fault trace at the distal end of the spit. The boreholes range in depth from 44 m (BH-4) to 33 m (BH-2), and each was terminated while still in unconsolidated sediments; bedrock was not reached in any of the boreholes. Drilling was terminated in BH-5 because of extensive caving at the surface. Drilling was terminated in BH-2, BH-3 and BH-4 when friction and the shear strength of the sediments at the bottom of the hole exceeded the torque of the drill rig.

A truck-mounted rotary drill rig was used for drilling, at first using 8-inch hollow-stem auger and a Shelby tube for recovery of undisturbed samples with sedimentary structures intact. This sampling method proved unworkable below the water table because pressure differentials between borehole and auger forced a sand-water slurry into the hollow auger stem. Liquefied sands that pooled inside the auger stem impeded sampling with the Shelby tube. Occasionally the Shelby tube itself became stuck in the sands inside the hollow-stem auger. When this occurred, the entire auger string had to be broken down and removed from the hole and the Shelby tube freed from the auger by repeated hammering and winching. Because of these problems, this drilling method was abandoned.

The drilling method susequently used is similar to that described by Kraft (1971) in which successive 5-foot sections of 6-inch solid-stem auger were corkscrewed into the ground (fig. 18). The corkscrewing method permitted the auger to penetrate sediments without actually lifting any sediment up the auger flite and minimized disturbance of the sedimentary record. However, corkscrewing was not always possible except near the surface and in easily penetrated sediments. The sedimentary record obtained from perfectly corkscrewed auger was best, but the record from auger sections that were partly rotated was nevertheless quite good. Lithologic changes were still readily discernible.

When the desired sampling depth was reached, the auger string was lifted vertically from the hole without rotation. The top sections of auger were removed one by one until the bottom sections with newly augered sediments were brought to the surface. These sediments were logged and sampled, and then the auger string was sent back down the

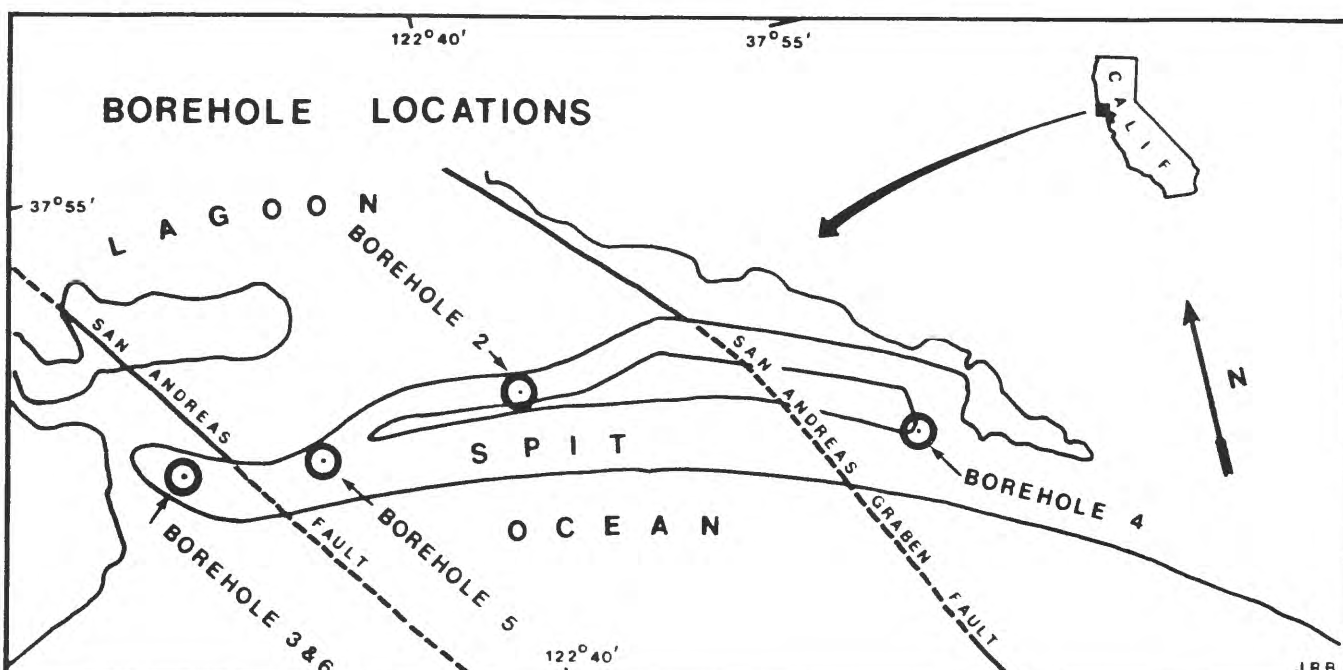


Figure 17. Index map of Stinson Beach spit showing locations of boreholes.

borehole. Because corkscrewing the auger string was only desirable for new portions of the borehole, the auger string was rapidly rotated back to the bottom, effectively cleaning the bottom auger sections and clearing the borehole as well. When the bottom was reached, rapid rotation was stopped, and corkscrewing into new sediments begun. The borehole was deepended by 10-foot intervals; thus two 5-foot sections of auger were added each time new material was to be drilled. Increments of only 10 feet minimized chances for binding the auger string and increased chances for recovery of more precisely located samples. Ten feet of corkscrewing into sediments was also usually near the torque limits of the drill rig, especially in deeper parts of boreholes and in very fine grained sediments with high-shear strength.

When the newly augered sediments were brought to the surface, they were logged and sampled while the auger hung suspended from the rig. The exterior portions of each core section were first cut away using wire cutters to expose undisturbed and uncontaminated sediment. Lithologies were logged: sediment color noted using a Munsell soil color chart; and representative sediment samples cut, bagged, and labeled according to location and depth. Separate megafauna and radiocarbon samples were taken wherever feasible. After the initial logging and sampling, the remaining portions of the core on the auger were systematically cut and searched for shells or other organic remains. After completion of drilling, boreholes were backfilled and excess spoils spread over the area.

Evidence of depositional environments from megafauna

Megafauna from the boreholes provide information on depositional environments and aid in interpretation of the depositional history of the Bolinas Lagoon area.

Megafauna, including (1) bivalves, (2) gastropods, (3) echinoids, (4) barnacles, (5) bryozoans, and (6) crustaceans, were collected from augered sediments and identified. Appendix B is a list of identified fauna with depths and sample numbers keyed to the borehole logs shown in plates 8 to 11. Shearing caused by auger rotation broke many of the larger shells, and in many instances only fragmentary remains were recovered. Some of the identifications were made on fragments representing less than half the original shell or valve, and this accounts for uncertain identifications (W.O. Addicott, written commun., 1976). Many specimens were unabraded with strong original coloration, whereas others were chalky or strongly abraded. In general, abraded shells were associated with coarse-grained sediments, and pristine shells with fine-grained sediments.

The preponderance of bivalves and low diversity of species together with known habitats of the species present indicate accumulation in a protected, fully marine, shallow to very shallow estuary or bay. Most of the bivalves and some gastropods are infaunal species that characteristically inhabit sandy substrates in protected, very shallow water environments (W. O. Addicott, written commun., 1976).

Figure 18a. U.S. Geological Survey mobile drill rig.

Figure 18b. Deepening borehole by cork-screwing 6-inch solid-stem auger.

Figure 18c. Logging borehole sediments.

With few exceptions, the fauna are characteristic of protected, open-coast, bay and estuarine environments. Ricketts and Calvin (1968) subdivided bay and estuarine environments into major subenvironments including (1) sand flats, (2) mud flats, (3) eelgrass flats, and (4) rocky shores. Taxa recovered from boreholes and commonly found in subtidal sand flats include (1) Clinocardium, (2) Macoma secta, (3) Tellina, (4) Transenella, (5) Olivella and (6) Dendraster. Those that typically inhabit intertidal mud flats include (1) Cryptomya, (2) Macoma nasuta, (3) Saxidomus, (4) Tresus, and (5) Nassarius. Typical dwellers of eelgrass flats include (1) Lacuna, (2) Mitrella, and (3) Nassarius. Several species that are generally restricted to a protected outer coast environment but not necessarily a bay or an estuary include (1) Hinnites, (2) Penitella, (3) Platyodon, (4) Nassarius, and (5) Tegula.

Some of the epifaunal species identified from boreholes typically live on a hard substrate, which may include compact sediments, rounded cobbles, other shells, or bedrock. The rock-clinging species include (1) Hinnites, (2) Mytilus, (3) Diodora, and (4) Balanus. A number of species typically inhabit rocky coastal areas, and these include (1) Modiolus, (2) Protothaca, (3) Acanthina, (4) Ceratostoma, (5) Diodora, (6) Nucella, (7) Searlesia, and (8) Tegula. Rock-boring or nestling bivalves are represented by (1) Penitella, (2) Petricola, (3) Platyodon, and (4) an undetermined pholadid fragment. Together these taxa indicate the proximity of a rocky shore or substrate. At present, Duxbury Reef, a wave-cut platform, lies approximately 2 km southwest of Stinson Beach spit; and a rocky, boulder-strewn coastline lies approximately 2 km southeast of the spit toward Rocky Point. Both these areas could have supported the species listed above that inhabit rocky shores and may have been source areas for transported shells. Rocky areas closer to the present site of Stinson Beach spit may now be buried under sediments in Bolinas Bay.

The taxa, considered both individually and in assemblages, indicate accumulation in shallow to very shallow water in a protected fully marine bay or estuary. The ubiquity of shallow-water species suggests that the Bolinas Lagoon area was never a deep-water embayment but continuously shallow. From this it can be inferred that for the past 8,000 years, sediment accumulation has generally kept pace with rising sea level in Bolinas Lagoon.

Borehole 2

Borehole 2 was drilled over the man-made extension of Stinson Beach spit that until the mid-1960's was a back-barrier area (fig. 17).

The bottom 19 m of borehole 2 consists of moderately to very poorly sorted, fine to medium sand with variable amounts of clay and silt that, because of their texture, appear to be mostly lagoonal deposits (pl. 8).

Above the 14-m level, gravelly sands are interbedded with fine to coarse sand and may indicate interfingering of lagoonal deposits with washover and beach-berm sediments. Sandy gravel and gravelly coarse sands occur in the 5.5 to 6.5 m segment and are probably beach or channel deposits. This gravel is overlain in the 2- to 5.5-m segment by pebbly, medium to coarse sand that may be washover, beach-berm, and dune deposits. The 1.5-to 2-m segment consists of organic-rich silty, clayey, medium sand that is interpreted as a back-barrier marsh deposit. The top 1.5 m of the borehole is dredged fill.

Borehole 3 & 6

The location of borehole 3 & 6 is approximately 0.5 km east of the inlet and 0.5 km west of the 1906 trace of the San Andreas fault (fig. 17).

The 22-to 36-m segment of borehole 3 & 6 consists of clayey, silty, fine to medium sand and clayey, sandy silt (pl. 9) deposited in a freshwater lake or pond. These deposits lack shells or other organic remains characteristic of the overlying sediments. The oyster *Ostrea lurida* was found in borehole 4 at the transgressive boundary; in borehole 3 & 6, *O. lurida* occurs at about the 20-m level, 2.5 m above the probable transgressive boundary. *O. lurida* was found nowhere else in any of the four boreholes. The textural differences between the deposits from 22 to 36 m and the finer grained lake or pond deposits in borehole 4 may be explained by the proximity of borehole 3 & 6 to Pine Gulch Creek, the major source of fluvial sediments from the Bolinas drainage. There is no evidence that indicates whether the freshwater areas in these two boreholes were connected.

Above the 22-m level is a complex series of shallow bay, lagoon, marsh and channel or beach deposits that extends up to the 8-m level. Immediately overlying the transgressive boundary at the 22-m level are pebbly, fine to medium sands that are overlain at the 17.5-m level by a 0.5-m-thick bed of clayey sandy silt that may be marsh deposits. These in turn are overlain by extremely poorly sorted clayey, silty, gravelly, fine to medium sand, which may be a mixture of beach or channel deposits and the underlying marsh(?) deposits. This 2-m-thick sequence of marsh deposits overlain by beach or channel deposits indicates a temporary shallowing of the depositional environment and may indicate that rates of sediment accumulation temporarily exceeded rates of sea-level rise.

In the 8-to 16-m segment, above the relatively coarse grained beach or channel deposits, the sediments become finer grained and consist of fine to medium sand with varying proportions of clay and silt. Texturally, these appear to be lagoonal deposits.

The 7-to 8-m segment consists of pebbly medium sands that may be washover or beach-berm deposits. Immediately overlying these are 3.5-m of gravelly, medium to coarse sand and sandy gravel containing rounded clasts up to 8 cm in diameter. These very poorly sorted deposits are similar to present-day deposits near the inlet and probably represent a similar high-energy environment.

The 0- to 4- m segment consists of interbedded channel gravels, washover, beach-berm and dune sand.

Borehole 4

Borehole 4, the deepest of the four boreholes at 44 m, is located at the eastern edge of the man-made lagoon on Stinson Beach spit (fig. 17).

The bottom 9 m of borehole 4 consists of very fine grained, organic-rich freshwater lake or pond deposits that are from 7,770±65 to perhaps more than 13,000 years old (pl. 10).

At about the 35-m level, there is a 1-m-thick segment of interbedded sandy, silty clay and clayey, silty, fine to medium sand that very likely represents interfingering freshwater and marine deposits and marks the transgressive boundary. A single radiocarbon date from shells at the 34.5-m level (USGS-171) places the marine incursion at approximately 7,770±65 years B.P.

Above the 34-m level in borehole 4 is a 12-m-thick sequence of fine to medium sand that may be lagoonal or nearshore to offshore deposits from a relatively shallow embayment.

Marine sediments from Bolinas Bay were taken with an orange-peel grab sampler and analyzed for grain size by Isselhardt, Osuch, and Wilde (1968). Their values for sorting and skewness were calculated according to formulae by Trask (1932), and kurtosis from the formula of Krumbein and Pettijohn (1938). These formulae are different from those derived by Folk and Ward (1957), which are used in this report, and result in different values for a given sample. Hence, values for grain-size parameters calculated in this report cannot be readily compared with those of Isselhardt Osuch, and Wilde (1968).

The average median grain size for 48 samples from Bolinas Bay is 3.25 phi (fine sand) with extremes ranging from 1.25 phi (medium sand) to 3.75 phi (very fine sand), and median grain size generally decreases seaward from Bolinas cliffs and Stinson Beach spit (Isselhardt and others, 1968; Wilde and others, 1969). Degree of sorting in most of these samples showed a negative correlation with increasing grain size. Skewness and kurtosis values, however, showed unsystematic geographic distribution (Wilde and others, 1969).

The 22-to 34-m segment of borehole 4 includes sediments with grain size and sorting similar to those for the samples from Bolinas Bay (append. A). This may indicate that for an undetermined period, the deposits overlying freshwater lake sediments in borehole 4 accumulated in a shallow marine embayment not unlike present-day Bolinas Bay.

This segment may thus represent a transgressive sequence with generally deepening water. The layer of clayey, silty, fine to medium sand at the 27-m level may indicate deposition either in (1) deeper, quiet water, or (2) shallow quiet water, for example, lagoonal. Above the 22-m level is a 3-m-thick layer of clayey, silty, fine to medium sand that indicates slightly lower energy conditions. This also may be interpreted as (1) sediment deposited in a deeper water environment than that of the underlying sands, or (2) deposits from a shallow-water, protected environment. The latter interpretation appears more tenable in view of the appearance of gravel-sized clasts above the 19-m level. Thus these fine-grained deposits may be lagoonal. It appears that a shallowing sequence begins at an undetermined point below the 22-m level and continues upward in the borehole. The medium to coarse sands that occur in the 7.5- to 14-m segment may be nearshore, beach-berm, or washover sediments. These are overlain by sandy gravel and gravelly, coarse sand in the 6- to 7.5-m segment that may be channel gravels similar to deposits presently found in Bolinas Lagoon inlet. At the 5.5 m level is a 15-cm-thick layer of organic-rich clayey silt that may represent back-barrier marsh deposits buried by indistinguishable sequences of beach-berm, washover, and dune sands. The top meter of the borehole consists of aeolian crossbedded dune sand.

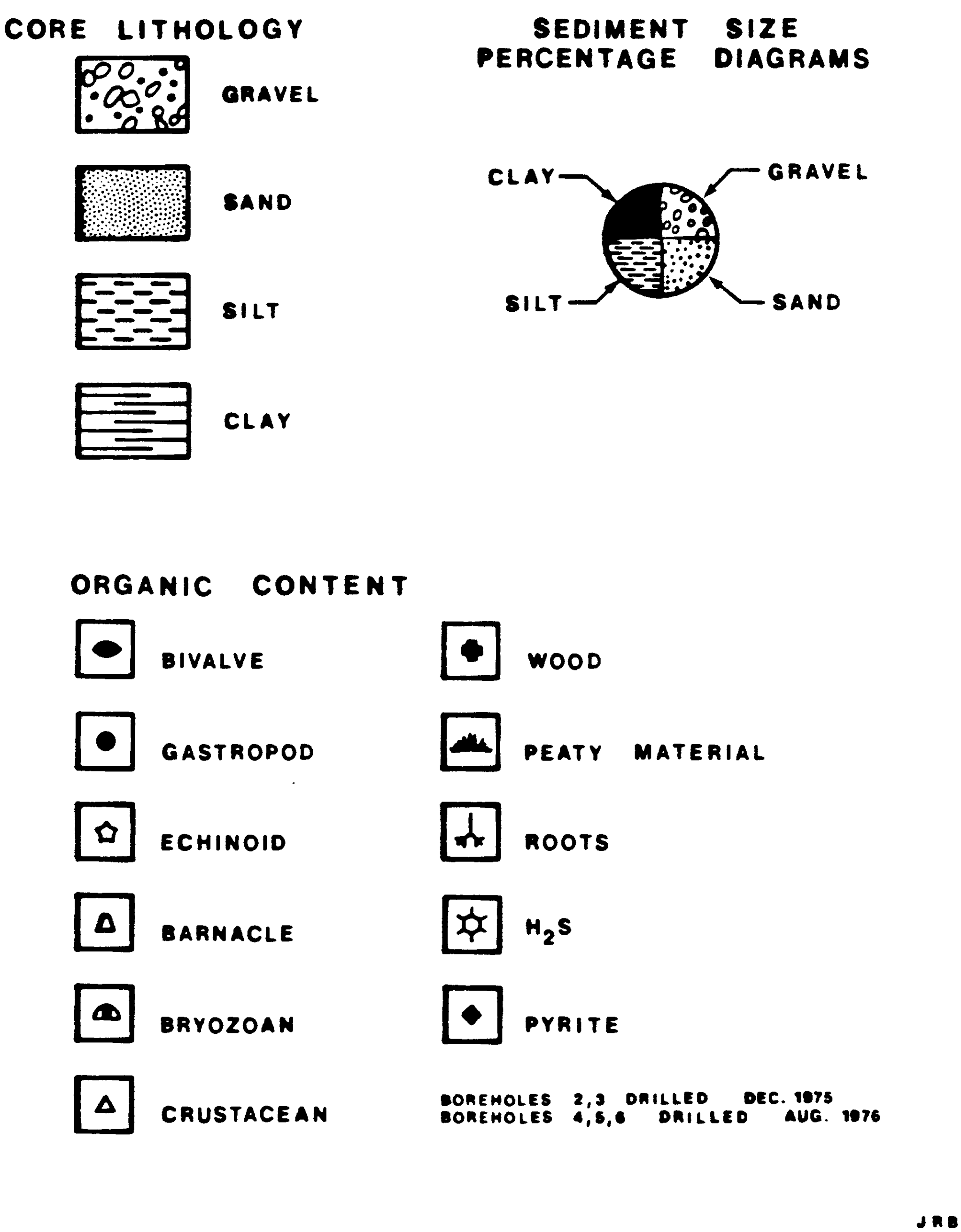
Borehole 5

Borehole 5 is located approximately 2 km east of the lagoon inlet (fig. 17).

Below the 17-m level, the sediments are interbedded, fine to coarse sands that contain variable proportions of clay and silt (pl. 11). Most of these deposits contain marine and estuarine mollusks and have textures suggesting accumulation in quiet-water, low-energy, probably lagoonal environments. Organic-rich, very fine grained deposits at the 20-, 22.5-, and 25-m levels contain woody fragments and may have accumulated in marshes. The alternating fine-grained and very-fine-grained deposits below the 17-m level suggest fluctuating bathymetry or energy but continuously shallow water.

The 2-to 17-m-borehole segment contains mostly interbedded fine to coarse sand, gravelly coarse sand, and sandy gravel. Textural parameters (append. A) suggest that these are very likely interbedded washover, beach, and berm deposits. The 7- to 8-m segment contains rounded clasts up to 10 cm in diameter, which may be channel gravel. The very well sorted, medium sands in the 0.5- to 2-m segment are probably aeolian deposits. The top 0.5 m of the borehole apparently consists of mixed aeolian and washover deposits.

FIGURE 19. EXPLANATION OF SYMBOLS SHOWN ON BOREHOLE LOGS



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Barrier Formation

Using borehole lithologies, it is difficult to determine the point at which a barrier first formed, creating the initial coastal lagoon. The deposits overlying the transgressive boundaries in boreholes 4 and 3 & 6 are similar to present-day sediments sampled in Bolinas Bay by Isselhardt, Osuch, and Wilde (1968). There is no evidence however to indicate that these could not also be lagoonal. Hence, it is possible that at the time of the marine transgression recorded in sediments below Stinson Beach spit, a barrier already existed.

The first lagoonal deposits in borehole 4 are younger than the freshwater-marine boundary dated at approximately 7,770±65 years B.P. In borehole 3 & 6, the first lagoonal deposits are at or below the 15-m level dated at 6,450±100 years B.P. Therefore, if the barrier did not exist prior to the time of transgression recorded in borehole 4, 7,770±65 years B.P., it apparently formed no later than 6,450±100 years B.P. It is possible that the barrier first formed when the strand line reached the terrace or hills that once extended southeast from Duxbury Point. The rising sea would then form a partly closed embayment or lagoon between this topographic high and Bolinas Ridge. The hills southeast of Duxbury Point have been eroded to form Duxbury Reef, a wave-cut platform that now extends approximately 3 km into Bolinas Bay, although only about 1 km of the reef is exposed at low tide. As the hills west of the ancient lagoon were eroded northward, forming Duxbury Reef and Bolinas Cliffs, the barrier presumably also migrated in that direction, in equilibrium with the adjacent coastline. With continual sea-level rise and coastal erosion, the lagoon and spit are moving landward and upward in space and time (Kraft and Allen, 1975).

The general upward changes in depositional environments are similar for the four boreholes, yet the detailed lithology of each is unique. Deposits differ widely in thickness, texture, and sequence. No two boreholes have the same sedimentary sequences, indicating geographic fluctuations of spatially restricted environments that left deposits having no lateral persistence along time planes.

Depositional environments are affected by numerous factors including: (1) changes in eustatic sea level including short-term oscillations, (2) tectonic or isostatic subsidence, (3) configuration of the barrier(s) and inlet(s), (4) coastline configuration, (5) size, location and sediment discharge of local streams, and (6) shoaling due to accumulation of sediments.

Each of the preceding factors presumably has caused changes in sedimentation through time at Bolinas Lagoon. This has resulted in complex sequences of transgressional-regressional deposits observed in the boreholes beneath Stinson Beach spit and explains why none of the boreholes shows an idealized transgressional sequence of deposits.

The ubiquity of shallow-water fauna, together with the preponderance of lagoonal or other shallow-water deposits beneath Stinson Beach spit, suggests that for the past 8,000 years accumulation of sediment has generally kept pace with rising sea level in the drowned valley.

Figure 22 shows an interpretive cross section through the four boreholes and indicates the relationship between the major faults, tectonic subsidence and major lithologic units determined from drilling.

Depositional record from small-diameter cores

Small-diameter cores were taken by hand in the lagoon and surrounding marshes that are inaccessible to the truck-mounted drill rig (fig. 20). Consolidated and sandy deposits were sampled with hand augers that consisted of (1) 2-inch and 4-inch diameter auger buckets, (2) 4-foot sections of pipe, and (3) a handle. Two types of buckets are used: sand buckets have a solid cylindrical wall and closed blades, whereas mud buckets have the cylinder walls partially cut away and open blades. Good lithologic and faunal samples can be obtained with this sampling technique, although sedimentary structures are usually obliterated by shearing. Effective sampling can only be accomplished when borehole walls resist collapse, and ends when layers of large gravel or cobbles are reached.

A Davis corer was used to sample unconsolidated silt and clay. This device consists of a sampler and 4-foot sections of detachable rod. The sampler consists of a pointed piston that fits inside a metal sleeve 2.5 cm in diameter. When the sampler is pushed down through sediments, the pointed end of the piston extends slightly beyond the enclosing tube. At the desired sampling depth, the piston is pulled up inside the sleeve by lifting the rod. The piston is then caught by a spring-loaded catch. The entire device is then pushed down into the sediment to a depth equal to the length of the sleeve, about 25 cm. The sampler is then withdrawn and the core extruded.

The Davis corer permits continuous or discontinuous sampling; the cores recovered are relatively undisturbed, and good lithologic and faunal samples can be obtained.

Cross section A-A′

The sediments cored along transect A-A′ (fig. 21) are all fine-grained lagoonal deposits that locally contain bivalves including *Macoma* sp. Cores 9-6-75-1, 9-6-75-2, 9-6-75-3, and 9-6-75-4 (fig. 20) consist of 1 to 2 m of clayey silt overlying sandy, clayey silt that grades downward into silty sand. The two westernmost cores have a thin layer of relatively clean fine sand at a depth of approximately 3 m. In core 9-6-75-4, this horizon is underlain by at least 5 m of silty clay that contains few bivalve fragments.

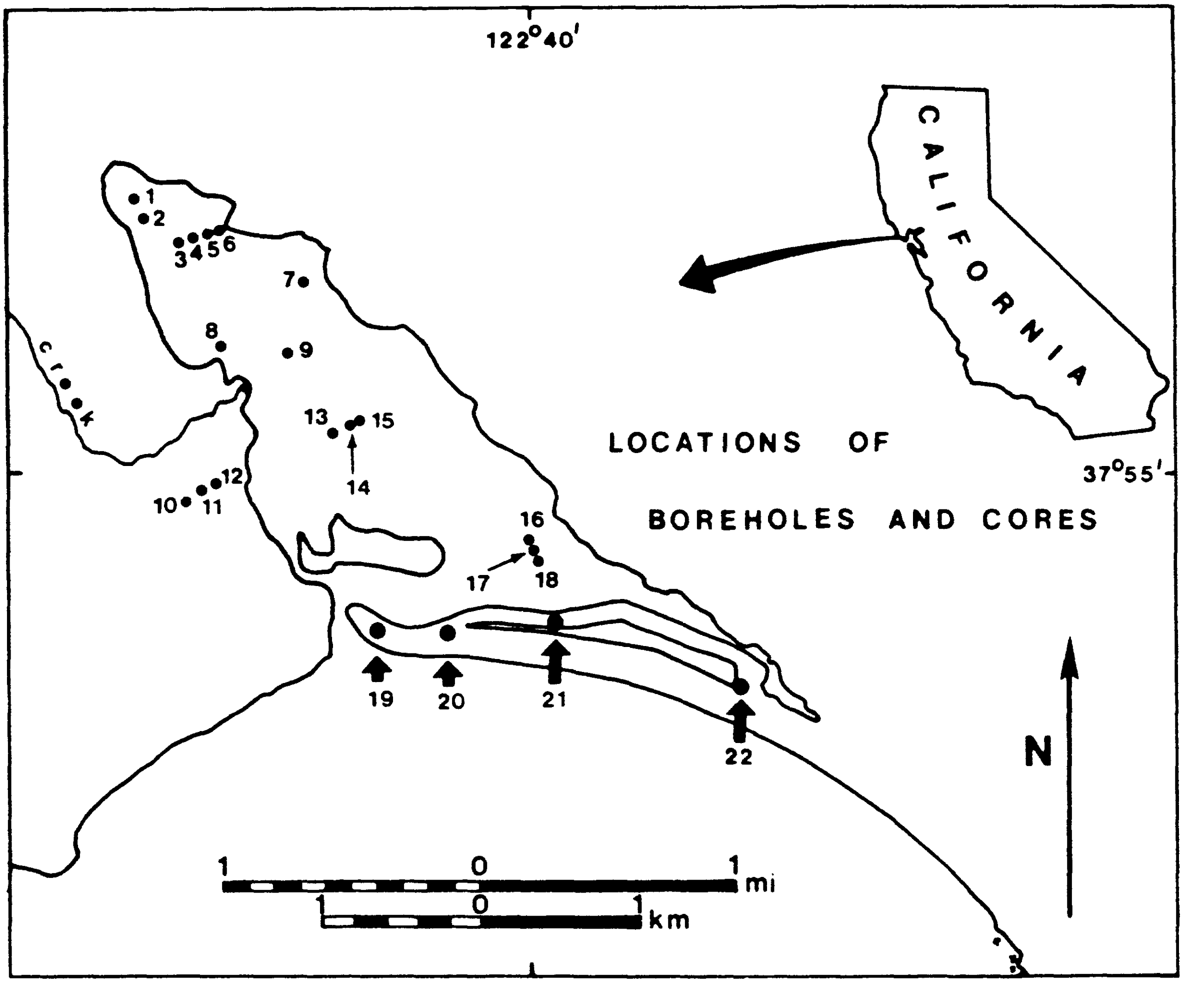


Figure 20. Locations of boreholes and cores. Coordinates and elevations of tops of boreholes and cores are listed in Appendix C.

Number	I.D. Number & Core Type		Number	I.D. Number & Core Type	
1	8-1-74-4	(Davis)	12	9-6-75-6	(hand auger)
2	6-76	(plastic tube)	13	9-9-75-3	-do-
3	9-6-75-4	(Davis)	14	9-9-75-2	-do-
4	9-6-75-3	-do-	15	9-9-75-1	-do-
5	9-6-75-2	-do-	16	2-21-76-2	-do-
6	9-6-75-1	-do-	17	2-21-76-1	-do-
7	8-24-75-1	(plastic tube)	18	2-21-76-3	-do-
8	8-1-74-3	(Davis)	19	Borehole 3&6	(rotary drill)
9	8-1-74-1	-do-	20	Borehole 5	-do-
10	9-20-75-1	(hand auger)	21	Borehole 2	-do-
11	9-6-75-5	-do-	22	Borehole 4	-do-

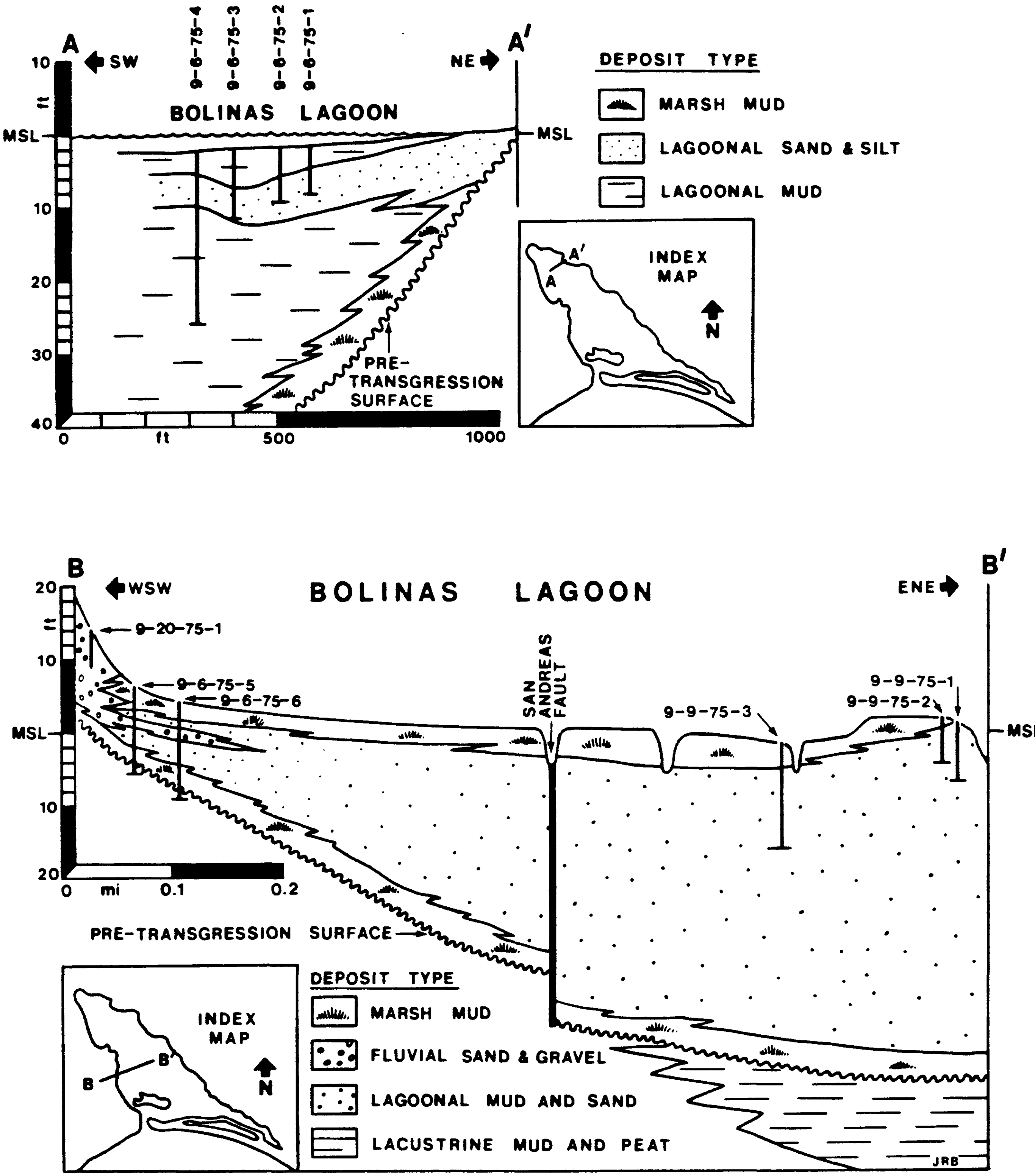


Figure 21. Interpretive cross sections showing Holocene environments of deposition in Bolinas Lagoon and nearshore areas.

The 1- to 2-m-thick sandy deposits indicate an environment of deposition different from the finer grained overlying and underlying deposits. This temporary, higher energy depositional environment may have been caused by (1) changing patterns of fluvial discharge, (2) changes in the configuration of the bay mouth barrier, or (3) a relative sea-level change whether eustatic or tectonically induced.

Cross section B-B′

The cores at the west end of transect B-B′ (fig. 21) include complex sequences of lagoonal, marsh, and fluvial deposits. Marsh deposits are characterized by fine-grained sediments containing abundant roots and rhizomes, and occasional wood fragments. Lagoonal deposits are also fine grained, but lack roots and rhizomes, and generally contain bivalves and gastropods. Fauna identified from these cores include Macoma nasuta and Nassarius sp. The taxa indicate the prior existence of intertidal mud flats at the west end of cross section B-B′ (fig. 21) and indicate that the lagoon once extended at least 350 m west of its present shoreline south of present-day Pine Gulch Creek delta.

The lagoonal and marsh deposits are interbedded with fluvial deposits that consist of (1) sandy and silty gravels, (2) pebbly, silty fine sand, and (3) gravelly, sandy silt. The apparently unsystematic sequences of fluvial deposits suggest they were deposited by a migrating stream, perhaps in a paleo-delta of Pine Gulch Creek.

Cores 9-6-75-5 and 9-6-75-6 (fig. 20) located near the west end of transect B-B′ (fig. 21) bottomed in clayey, sandy pea gravel that contained rounded clasts and weathered lithic fragments up to 2 cm in diameter. These poorly sorted deposits are apparently weathered, well-consolidated, and varigated with reddish-brown iron straining that suggests subaerial exposure. These deposits may thus represent a paleo-soil developed on fluvial or deltaic deposits. The physiography of the low, flat area south and west of present Pine Gulch Creek delta and extending to the edge of Bolinas Mesa (pl. 1) indicates that it may be stream cut and suggests that this area may be largely underlain by stream deposits.

Transgressive-regressive sequences are indicated in cores 9-6-75-5 and 9-6-75-6. In each of these, the gravelly paleo-soil is overlain by a succession of (1) marsh deposits, (2) lagoonal deposits, and (3) marsh deposits (fig. 21). It can be inferred that as sea level rose, the paleo-soil was covered first by fringing salt marshes; then as the water deepened at least to intertidal levels, the salt marshes were inundated and covered with muds in which typical shallow-water estuarine species of mollusks thrived. After a short period of time, rates of sediment accumulation apparently exceeded deepening due to sea-level rise, and the area filled with sediments, once again becoming salt marsh. In turn, the most recent salt marshes were in part covered by stream deposits and slope wash.

Farther east along transect B-B′, at core 9-9-75-3 (fig. 21), a regressive sequence is evident and consists of approximately 2.5 m of discontinuous marsh deposits overlying silty fine sands and sandy silts. The underlying deposits locally contain abundant bivalve and gastropod shells and indicate lagoonal, perhaps intertidal conditions. Intermittent thin sand lenses in the cores may be fluvial sediments from Pine Gulch Creek deposited during periods of exceptional flow.

The underlying paleo-soil that developed on stream gravel lies from 1.5 to 2.5 m below present MSL in cores 9-6-75-5 and 9-6-75-6, and this shallow-lying surface suggests that the incursion of the lagoon in this area occurred relatively recently. The extremely thin lagoonal deposits here, from 0.5 to 1.2 m, further indicate that this western extension of Bolinas Lagoon was relatively short-lived. The effects of tectonics on the depositional sequences in these cores is not known.

Cross section D-D′

A cross section extending southeast from the head of the lagoon through Stinson Beach spit passes through cross sections A-A′ and B-B′ and indicates relationships among major sediment types identified in small-diameter cores and boreholes (fig. 23). In general, it shows a transgressive sequence of marsh, lagoonal and beach-barrier sediments overlying the pre-transgression surface that is in part underlain by lake or pond deposits. In the central part of the lagoon, Pine Gulch Creek and associated fringing marshes are interpreted as generally increasing in extent upward through time. With continued erosion of the Bolinas Cliffs and rising sea level, the shoreward progression of sedimentary units will continue.

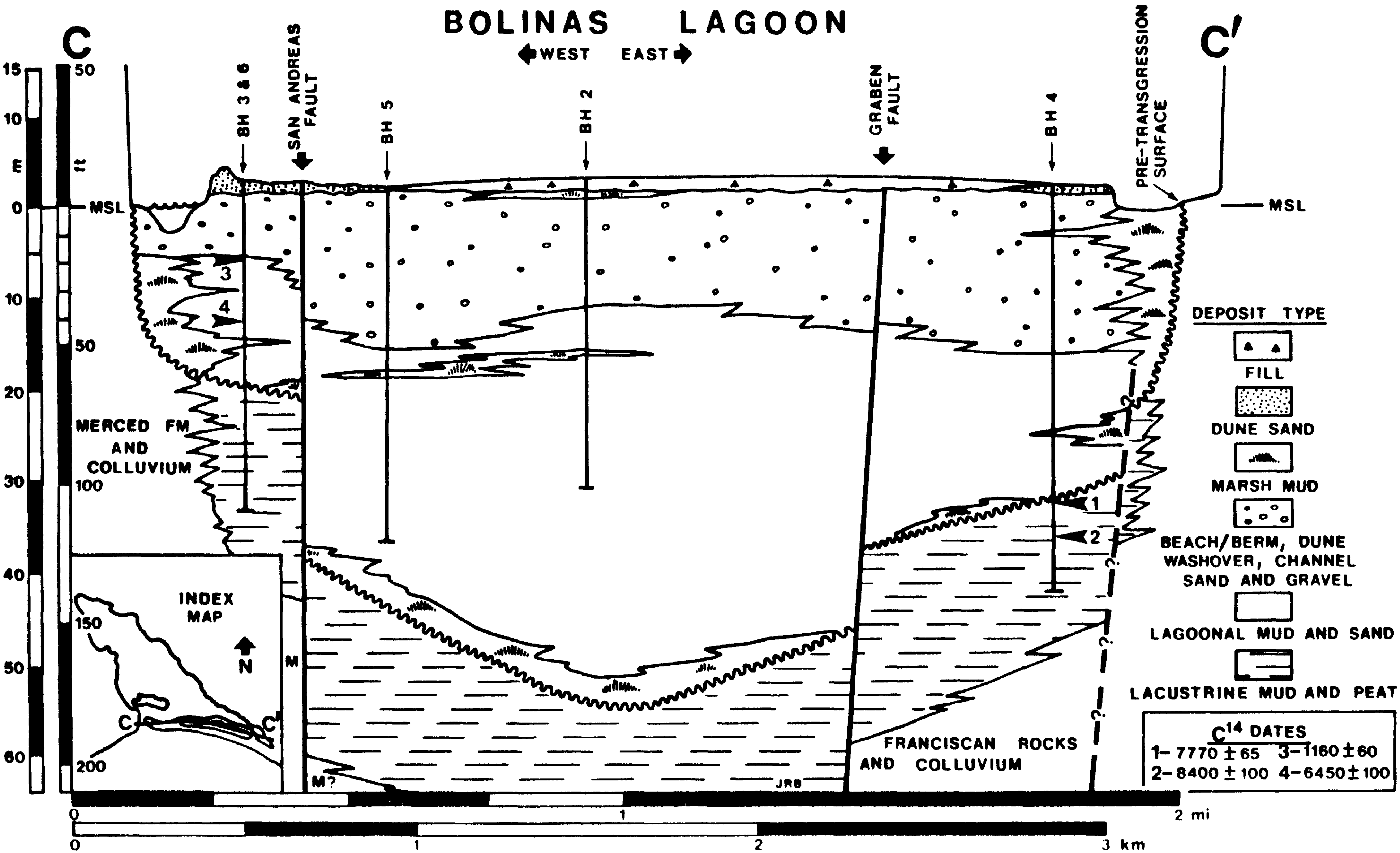


Figure 22. Interpretive cross-section approximately along the axis of Stinson Beach spit showing relationship of sedimentary units and faults.

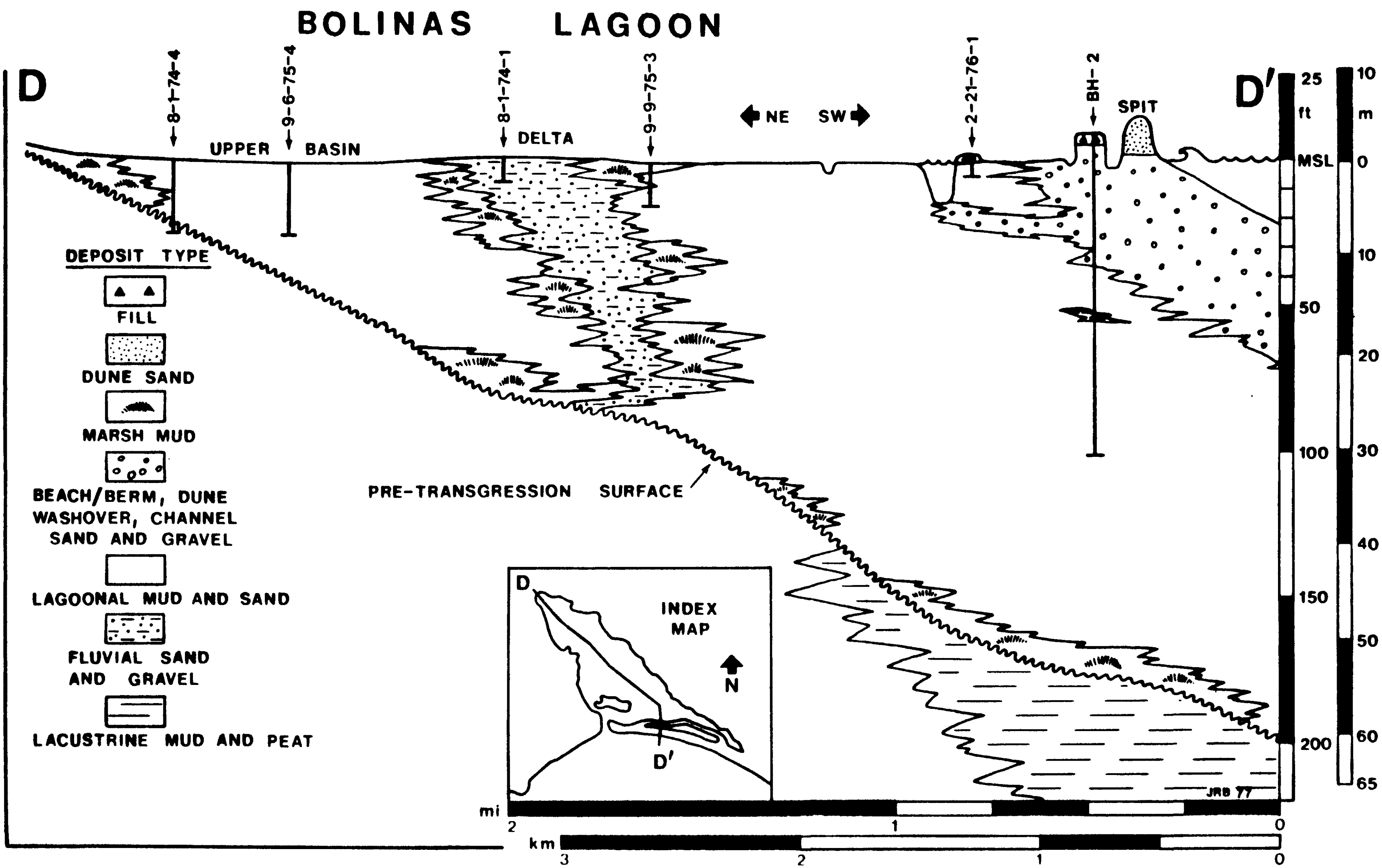


Figure 23. Interpretive cross-section of Bolinas Lagoon showing relationships of Pleistocene(?)-Holocene deposits.

TECTONIC SUBSIDENCE

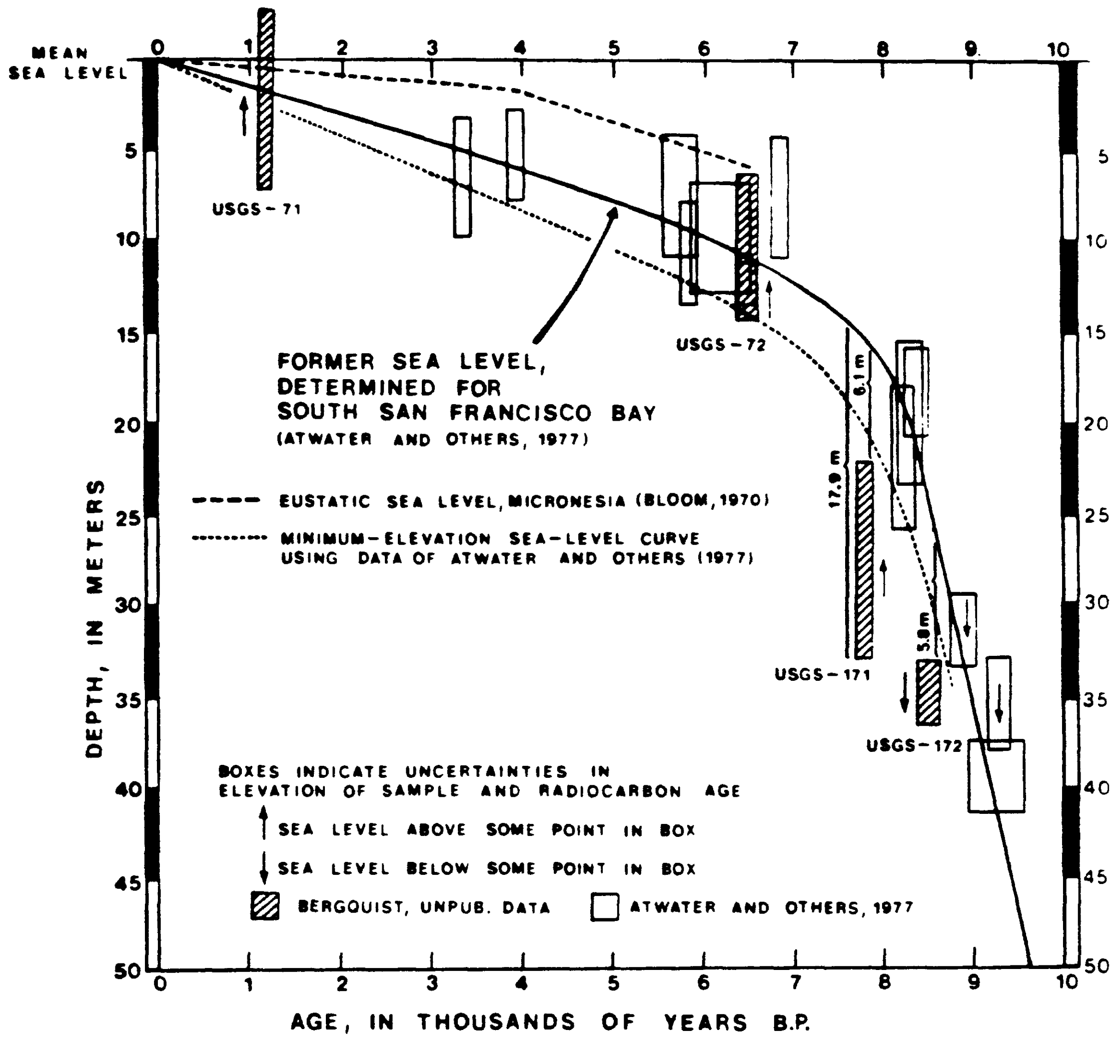
Comparison of the elevations of radiocarbon-dated subsurface samples from boreholes, with a curve of relative sea level for the past 10,000 years, permits measurement of apparent vertical displacement. Several authors have constructed curves of eustatic sea level (Fairbridge, 1961, 1966; Shepherd, 1964; Milliman and Emery, 1968; Bloom, 1970; Scholl and others, 1969; Emery and others, 1971), but the curve by Atwater and others (1977) is best suited for use in this study because of the proximity of the area for which it was constructed. This relative sea-level curve (fig. 24) was made on the basis of 13 radiocarbon dates from deposits beneath southern San Francisco Bay. Shifting sea level may account for part of the point-scatter, but because of the relatively few points and the magnitude of the uncertainties in elevation and age, no resolution of low-amplitude sea-level oscillations was possible (Atwater and others, 1977). A smoothed curve was thus visually fitted to the data points.

From approximately 8,500 to 6,500 years B.P., the slope of the sea-level curve changes from -4.6 to -0.3 (fig. 24) and indicates a decreasing rate of sea-level rise. The apparent reason for this change is the completed melting of the Laurentide, Cordilleran and Scandinavian ice sheets by 6,500 years B.P. (Bloom, 1971). Sea level in southern San Francisco Bay rose an average of 2 cm/yr from 9,600 to 8,000 years B.P. and rose 0.1 to 0.2 cm/yr from 6,000 years B.P. to the present (Atwater and others, 1977). The determination of tectonic displacement of sediments underlying Stinson Beach spit rests on the assumption that eustatic sea-level histories of Bolinas Lagoon and southern San Francisco Bay are similar.

Each box shown in figure 24 represents one radiocarabon date. The width represents the analytical uncertainty, one standard deviation (σ) on either side of the apparent age. Other uncertainties discusssed below may affect the age of samples, but because they are indeterminate and probably small, they are ignored in this study.

Elapsed time between death of the organisms used for dating and their accumulation will result in a date older than the enclosing sediments. The nature of the materials dated for this study and their environments of accumulation indicate that any hiatus is probably very short, and therefore negligible.

Carbon exchange after deposition will result in younger apparent ages. For this study it is assumed that exchange of carbon between shells or peat and their environments did not occur after death, although in fact such exchange may have occurred. In samples of equivalent age, carbon exchange will be greater for shells than for peat because $CaCO_3$ is chemically more reactive (Mangerud, 1972). Whole shells were burned for USGS-71, USGS-72, and USGS-171. This may result in slightly younger apparent ages because carbon exchange during



USGS RADIOCARBON LABORATORY NO.	DATED MATERIAL	AGE, IN YEARS B.P.	APPARENT TECTONIC DISPLACEMENT (m)	
			MIN	MAX
USGS - 71	SHELLS	1180 ± 60	N.I.*	N.I.
USGS - 72	SHELLS	6450 ± 100	N.I.	N.I.
USGS - 171	SHELLS	7770 ± 65	6.1	17.9
USGS - 172	PEAT	8400 ± 100	5.8	14.8

*NONE INDICATED

Figure 24. Tectonic subsidence indicated by comparison of radiocarbon dates from beneath Stinson Beach spit with relative sea-level curve for southern San Francisco Bay. Figure modified after Atwater and others (1977).

recrystallization probably occurs first in the exterior parts of shells (Mangerud, 1972). Practicality aside, the accuracy of shell dates theoretically would have been enhanced if only interior parts of shells were dated.

Uncertainties in relating sample elevation to the relative sea-level curve come from three principal sources: (1) uncertainty in determining present sample elevation, (2) uncertainty in determining sample elevation at time of deposition, and (3) uncertainty in determining amount of postdepositional subsidence (Atwater and others, 1977).

Total uncertainty of present sample elevation probably does not exceed ± 0.5 m and is the sum of uncertainties in (1) surveyed elevation of the tops of boreholes, (2) depth of sampling intervals in the borehole, and (3) position of dated material within each sampling interval (Atwater and others, 1977).

The elevation of shell samples relative to coeval sea level is determined primarily by depth ranges and habitats of similar living species. USGS-171 consisted entirely of shell fragments of *Ostrea lurida* (native Pacific oyster), which commonly lives in the low intertidal zone on hard or rocky substrates (Ricketts and Calvin, 1968; Keen and Coan, 1974). The intertidal range at Bolinas Bay is approximately 2.5 m today (National Ocean Survey, 1976) and is assumed to be the same at the time of accumulation of the shell samples.

USGS-71 and USGS-72 both contained shells of *Macoma nasuta* and *Tresus* sp. Both species typically inhabit intertidal to shallow-water subtidal environments (Moore, 1958; Ricketts and Calvin, 1968). USGS-72 also included shells of *Clinocardium nuttalli* and *Protothaca staminea*. *C. nuttalli* is an intertidal species, which commonly inhabits sand flats of bays and estuaries (Ricketts and Calvin, 1968); *P. staminea* inhabits the middle-intertidal zone, being commonly found in tide pools along rocky coasts or beneath the surface of packed mud or sandy to clayey gravel in protected areas of the outer coast (Ricketts and Calvin, 1968). Thus, the habitat of both USGS-71 and USGS-72 is likely intertidal, yielding an uncertainty in elevation of about 2.5 m. The additional species in USGS-72 render the interpretation of an intertidal habitat more certain than for USGS-71. To account for possible subtidal habitats of the dated bivalves, 1.5 m is added to the uncertainty in elevation of USGS-72, and because of its less certain intertidal habitat, 3.0 m is added for USGS-71. The uncertainty in elevation at the time of accumulation for USGS-71 is thus approximately 5.5 m, and 4.0 m for USGS-72.

Postdepositional compaction of sediments

Postdepositional compaction of sediments underlying the dated samples lowers their elevation relative to coeval sea level. Two major variables determine the amount of postdepositional compaction: (1) the degree of compaction for each underlying type of sediment, and (2) the thickness of each sediment type.

The top 22 m of deposits in borehole 3 & 6 consist primarily of silty sand, sand, and gravel. Below 22 m the sediments are finer grained and consist of clayey, silty sand and clayey, sandy silt that apparently lack both megafauna and peaty material (pl. 9). Sand is almost incompressible under moderate pressures (Weller, 1959), although Athy (1930) reported that vibrations can cause a reduction in volume of up to 11 percent in loose sand. The compacted, or equilibrium, state of sand is probably achieved rapidly in a seismically active area such as Bolinas where episodic seismic vibrations occur.

The interstices in sands below the uppermost-dated horizon of borehole 3 & 6 are filled with silt-sized particles and minor amounts of clay (pl. 9, append. A). The compressibility of these sediments will likely be lower than that of sand. Therefore, for this study, the effects of compaction of sediments above 22 m in borehole 3 & 6 in decreasing the elevation of dated samples are considered to be negligible.

Silt and clay will compact in varying degrees and result in elevations of samples lower than at the time of accumulation, and allowances must be made for this when using radiocarbon dates to determine vertical tectonic displacement.

The finest grained sediments in borehole 4 below the uppermost-dated horizon (USGS-171) are silty clay and clayey silt. Silty clay has a porosity of between 40 and 50 percent prior to compaction (Weller, 1959). Using one-half the compressibility of mud with 80 percent porosity overlain by 35 m of overburden given in Weller (1959), 10 m of silty clay will theoretically represent a column of sediment that has undergone 15 to 20 percent compaction. The original column height would thus have been 11.8 to 12.5 m, and the subsidence 1.8 to 2.5 m for USGS-171 (fig. 24). Most sediment below USGS-171 is clayey silt rather than silty clay (append. A), and this would indicate lower compressibility and less subsidence than calculated above. Below 37 m, however, an offsetting factor enters. At this point peaty material is encountered and comprises 2 to 4 percent of sample dry weights. Muds containing peaty material will compact more than similar non-organic sediments because of (1) the initial high porosity and low density of peat, and (2) the loss of volume due to decomposition of organic material (Kaye and Barghoorn, 1964). In general, the higher the clay content in a peaty clay, the lower its compressibility; and as amounts of silt and sand increase, compressibility further decreases (Kaye and Barghoorn, 1964).

If an additional 10 percent is added to the compressibility of silty clay, given above, to allow for compaction of peat, then the column height below USGS-171 would have been 13.3 to 14.3 m prior to compaction and subsidence 3.3 to 4.3 m. These figures probably represent liberal estimates of compaction for the peaty, clayey silt in borehole 4. Below USGS-172, the subsidence due to compaction of sediments would be 2 to 2.5 m.

The finest grained sediments beneath USGS-71 and USGS-72 in borehole 3 & 6 consist of clayey, sandy silt and clayey, silty, fine sand. Each of these sediment types has a lower compressibility than the 15 to 20 percent estimated for silty clay. To estimate compaction of these sediments, a range of 10 to 15 percent compressibility is used, and indicates approximately 2- to 3-m subsidence for USGS-71 and 1.5 to 2.5 m for USGS-72.

The above values of subsidence due to compaction of sediments in boreholes 3 & 6 and 4 were made on the basis of sediments actually drilled. Additional thicknesses of underlying sediments will increase these figures.

One problem with using percentage compaction figures is that a column of relatively homogeneous sediment may differentially compact under load. As sediment is added to a column from above, the underlying deposits make a slow, continual adjustment to the added weight. The lowest parts of a column may thus reach compacted equilibrium before deposition of higher parts. Calculation of the original elevation at which a given horizon in a column accumulated through use of percentage compaction, figures will therefore result in an elevation higher than the true figure. Elevations of accumulation determined with this method should therefore be regarded as maximum figures and interpreted accordingly.

Measurements of subsidence

The distance between the eustatic sea-level curve and the depth of radiocarbon-dated samples (fig. 24), which cannot be accounted for in the previously discussed uncertainties (table 2), is assumed to be the result of tectonic subsidence.

Borehole 3 & 6 is located approximately 150 m southwest of the 1906 trace of the San Andreas fault. Because USGS-71 and USGS-72 plot on or near the relative sea-level curve of Atwater and others (1977), there is no indication of tectonic subsidence in this borehole within the past 6,450±100 years.

The two dated horizons in borehole 4 do indicate apparent tectonic displacement. Despite large uncertainties in elevation, the position of USGS-171 indicates 6.1 to 17.9 m of tectonic displacement, and USGS-172 indicates 5.8 to more than 14.8 m.

Because the peaty material of USGS-71 accumulated above coeval MSL, the maximum tectonic subsidence cannot be accurately determined. However, a rough minimum estimate of the elevation at which USGS-172 accumulated can be made by subtracting the apparent minimum tectonic offset of this sample from that of USGS-171. This indicates that the bottom of the lake or pond in which USGS-172 accumulated was at least 0.3 m above coeval MSL.

Table 2. *Data for Radiocarbon Dates, Elevations, Sea Level, and Tectonic Subsidence*

Borehole number	3 & 6	3 & 6	4	4
U.S.G.S. radiocarbon laboratory sample number[1]	USGS-71	USGS-72	USGS-171	USGS-172
Material dated	Bivalves: Macoma nasuta (Conrad) Tresus sp.	Bivalves: Clinocardium nuttali (Conrad) Macoma nasuta (Conrad) Protothaca staminea (Conrad) Tresus sp.	Bivalve: Ostrea lurida Carpenter	Reddish-brown, fibrous peaty material
Environment of accumulation	Intertidal to shallow-water subtidal	Intertidal to shallow-water subtidal	Intertidal to shallow-water subtidal	Lake or pond
Radiocarbon date in years B.P.	1170 ± 65	6450 ± 100	7770 ± 65	8400 ± 100
Present sample elevation (E_p) (meters)	-6.5 ± 0.7	-13.7 ± 0.5	-32.5 ± 0.5	-35.9 ± 0.7
Uncertainty of sample elevation at time of accumulation (E_a) (meters)	2.7 ± 2.7	2 ± 2	2.7 ± 2.7	>0.3 above MSL[2]
Postdepositional compaction of underlying sediments (C) (meters)	2.5 ± 0.5	2 ± 0.5	3.8 ± 0.5	2.2 ± 0.2
Sea level, Bolinas Bay (S_b)[3] (meters)	>-2.3 ± 4.9	>-10.2 ± 4.0	>-27.3 ± 5.4	>-34.5 ± 1.8
Sea level, southern San Francisco Bay (S_s) (meters)	-1.7 ± 0.1	-10.6 ± 0.2	-15.3 ± 0.5	-24.2 ± 2.7
Apparent tectonic subsidence using sea-level curve of Atwater and others (1977) for comparison (T)[4] (meters)	none indicated	none indicated	6.1 to 17.9	5.8 to >14.8

[1]Dates by Stephen Robinson, U.S. Geological Survey, Menlo Park, Calif.
[2]Elevation cannot be determined accurately because of accumulation above coeval mean sea level (MSL).
[3]$S_b = E_p + E_a + C$
[4]$T = S_s - S_b$

Another method of measuring tectonic displacement is to compare elevations of the transgressive boundary in borehole 3 & 6 and 4 (pl. 9, 10). Assuming (1) the transgressive boundary occurs in borehole 3 & 6 at the 22-m level (20 m below MSL), (2) the transgressive boundary occurs in borehole 4 at the 35-m level (33 m below MSL), and (3) the elevations of these points were formerly the same, then there has been 13-m more subsidence in borehole 4 since 7,770±65 years B.P.

Although borehole 4 lies 275 m east of the projection of the graben fault indicated by seismic profiling (fig. 17, pl. 5), it appears that there has been vertical tectonic displacement there. One or more normal faults not determined by seismic profiling may be concealed east of borehole 4 (fig. 22), although after the 1906 earthquake there was no reported surficial expression of the hypothesized fault(s).

Part of the subsidence may be due to isostatic adjustments to a minimum 45 m of overburden. However, if isostatic subsidence has occurred, it probably represents only a very small fraction of the total vertical movement because the overburden is relatively thin.

The smoothed sea-level curve (fig. 24) by Atwater and others (1977) represents an optimal fit to the data; however, there are other possible positions of the curve. Because the Atwater curve may reflect tectonic and isostatic subsidence, probable upper and lower limits for the sea-level curve have been added in figure 24 in order to measure maximum and minimum tectonic subsidence of dated horizons in borehole 4. The lower limit is a visually fitted curve, and the upper limit is a eustatic sea-level curve based upon data from the Eastern Caroline Islands (Bloom, 1970). This curve is based upon dates from small oceanic islands that are presumably free of isostatic downwarp that may have affected continental shelves in response to postglacial water loading. It therefore may be a truly eustatic sea-level curve. Although it extends back only 6,500 years B.P., the difference in elevation between Bloom's curve at that time and the sea-level curve by Atwater, Hedel, and Helley (1977), 5 m, is extrapolated back to 8,400±100 B.P. in order to measure maximum tectonic subsidence at Bolinas Lagoon. Using the upper and lower sea-level curves, the apparent tectonic subsidence is (1) 1.3 to 23 m for USGS-171, and (2) 1.3 to more than 14.8 m for USGS-172. No maximum value can be measured for USGS-172 because this sample accumulated above coeval MSL.

ENVIRONMENTAL AND PALEOCLIMATIC SIGNIFICANCE OF FOSSIL POLLEN FROM BENEATH STINSON BEACH SPIT

Fossil pollen was recovered from six samples between the 27.5-m and 44-m levels in borehole 4 (pl. 10) from peaty, silty clay, and peaty, clayey silt. Only fine-grained sediments were chosen for pollen analysis because coarser grained sediments, including those above 27.5 m, were assumed to be winnowed (pl. 10). Standard techniques of pollen extraction (Faegri and Iversen, 1975) were used and are outlined in another section of this paper. Forty-two pollen types were counted; the greatest concentrations of pollen were found at the 44- and 43-m levels, and the smallest concentrations at the 35- and 27.5-m levels (table 3). Differences in pollen concentration may result from (1) changes in rates of sediment accumulation, (2) differential preservation of pollen, or (3) changes in the amount of pollen rain. Plates 12 and 13 illustrate the distribution of fossil pollen by frequency per cm^3 and percent of the total pollen within each sample. By plotting the percent frequency of pollen within each sample, differences in curve geometry resulting from variable dilution of pollen caused by different rates of sediment accumulation are eliminated. Thus, given a constant pollen rain, the resulting pollen curves of percent frequency are theoretically independent of sediment accumulation rates.

Pollen nomenclature and abbreviations

Plant nomenclature in this paper follows Munz and Keck (1973), although there are several exceptions to this. Compositae A includes the high-spine pollen types of the sunflower family (the largest family of vascular plants), and Compositae B includes the low-spine pollen types. Liguliflorae is a subdivision of Compositae made by Faegri and Iversen (1975). The Cheno-am category includes pollen from two families: Chenopodiaceae (goosefoot family) and Amaranthaceae (amaranth family). TCT includes pollen from three families of conifers: Taxaceae (yew family), Cupressaceae (cypress family), and Taxodiaceae (redwood/giant sequoia family). The preponderance of TCT pollen at this site is probably from *Sequoia sempervirens* (redwood), and the TCT curve thus probably represents the record of *S. sempervirens*, although Cupressaceae such as *Cupressus*, *Juniperus*, and *Libocedrus* may also be represented. The Indeterminate category consists of pollen grains, which were not identified in this study, and the Unknown category consists of pollen grains, which were unidentifiable because of damage or deterioration. AP refers to arboreal pollen, and NAP to nonarboreal pollen.

Environmental and paleoclimatic interpretations

Changes in the fossil-pollen record through time result from changing local environment and long-term regional climatic change. In some instances, the presence of certain plant genera may alone be diagnostic of a particular climatic zone. In most cases, though,

TABLE 3. Pollen frequency in number per aliquot[1] and percent[2] of total pollen

Pollen Type	Borehole level (in meters) ➡ 27.5	35	38	41	43	44
ALGAE						
Botryococcus spp					+ (+)	
Pediastrum spp				1 (+)		21 (2)
LEPIDOPHYTA						
Isoetes spp (quillwort)			2 (1)	4 (1)	8 (2)	34 (3)
Selaginella spp (little club-moss)				1 (+)		
PTEROPHYTA (ferns)						
Botrychium spp (grape fern)				1 (+)	1 (+)	3 (+)
Dryopteris spp (wood fern)	1 (3)	1 (3)	3 (1)	3 (1)	2 (+)	29 (3)
Pteridium spp (bracken)			2 (1)	2 (+)	4 (1)	18 (2)
CONIFEROPHYTA (cone-bearing plants)						
Ephedra nevadensis Wats. (Mormon tea)			1 (+)			
Picea sitchensis (Bong.) Carr. (Sitka spruce)					27 (8)	17 (2)
Pinus spp (pine)	8 (25)	4 (11)	53 (21)	81 (26)	15 (5)	190 (20)
TCT (taxodium family, cypress family, yew family)	3 (9)	4 (11)	25 (10)	19 (6)	19 (6)	53 (5)
ANTHOPHYTA (flowering plants)						
Dicotyledoneae						
Acer spp (maple)	3 (9)	6 (16)	9 (4)	9 (3)	10 (3)	33 (3)
Aesculus sp (buckeye)					1 (+)	1 (+)
Alnus spp (alder)	1 (3)	5 (13)	18 (7)	12 (4)	20 (6)	63 (6)
Ambrosia spp (ragweed)					3 (1)	
Arceuthobium spp (in mistletoe family)				1 (+)	1 (+)	4 (+)
Artemisia spp (sagebrush)			1 (+)	4 (1)	4 (1)	5 (+)
Caryophyllaceae (pink family)						3 (+)
Castanopsis spp (chinquapin)						1 (+)
Ceanothus spp (Calif.-lilac)						4 (+)
Cehno-am (goosefoot family, amaranth family)	1 (3)	1 (3)	32 (13)	8 (3)	8 (2)	14 (1)
Compositae A (high-spine pollen, sunflower family)	2 (6)	3 (8)	30 (12)	28 (9)	17 (5)	70 (7)

Compositae B (low-spine pollen, sunflower family)				2 (+)		
Ericaceae (heath family)				1 (+)		
Eriogonum spp (wild buckwheat)						4 (+)
Liguliflorae (in sunflower family)						3 (+)
Lithocarpus spp (tanbark-oak)			2 (1)	1 (+)	1 (+)	3 (+)
Malvaceae (mallow family)					1 (+)	
Myricaceae (wax-myrtle family)			1 (+)	3 (1)	2 (+)	1 (+)
Papaveraceae (poppy family)	1 (3)			2 (+)	2 (+)	4 (+)
Plantago spp (native plantain)			1 (+)			7 (1)
Polygonaceae (buckwheat family)	1 (3)					
Quercus spp (oak)	2 (6)	1 (3)	10 (4)	7 (2)	14 (4)	27 (3)
Rhamnaceae (buckthorn family)				2 (+)	1 (+)	5 (+)
Rosaceae (rose family)			2 (1)	1 (+)		1 (+)
Rumex spp (native sorrel)					2 (+)	
Salix spp (willow)		1 (3)	1 (+)	8 (3)	17 (5)	38 (4)
Umbelliferae (carrot family)			1 (+)	1 (+)	2 (+)	2 (+)
Monocotyledoneae						
Cyperaceae (sedge family)			5 (2)	65 (21)	110 (33)	151 (16)
Gramineae (grass family)	2 (6)	3 (8)	8 (3)	11 (4)	15 (5)	38 (4)
Triglochin spp (arrow-grass)	1 (3)	1 (3)		1 (+)	1 (+)	10 (1)
Typha spp (cat-tail)			1 (+)			
INDETERMINATE	3 (9)	3 (8)	14 (6)	10 (3)	9 (3)	53 (5)
UNKNOWN	3 (9)	5 (13)	28 (11)	23 (7)	12 (4)	63 (6)
AP	20 (63)	24 (63)	126 (50)	148 (47)	134 (41)	442 (45)
NAP	9 (28)	12 (32)	88 (35)	131 (42)	177 (54)	415 (43)
TOTAL	32 (*)	38 (*)	250 (*)	312 (*)	330 (*)	973 (*)

[1]Aliquot: 27.5m = 1/178 · 35m = 1/150; 38m = 1/78; 41m = 1/56; 43m = 1/108; 44m = 1/32
Aliquot multiplied by frequency yields concentration per cm^3.

[2]Percent given in parentheses

*Total percent may not equal 100 because of rounding

+less than 1 percent

interpretations must be made from assemblages of fossil pollen and trends in vertical distribution. The validity of environmental reconstruction rests on the assumption that growth requirements and habitats of modern plants are the same as for similar fossil species.

Implications of Picea Pollen

The presence of 2 to 8 percent Picea (spruce) pollen in the 44- and 43-m levels, respectively, strongly suggests that a cooler, moister climate once existed in the vicinity of Bolinas. The Picea pollen is probably primarily from P. sitchensis (Sitka spruce), which presently ranges from Alaska as far south as Mendocino County, Calif. (Munz and Keck, 1973). The present Picea sitchensis forest zone extends almost continuously along a relatively narrow strip of coast throughout its range. The width of the zone ranges from a few kilometers to about 20 km, except where it extends inland up river valleys, and on the Olympic Peninsula where it is as much as 50 km wide. P. sitchensis generally grows at elevations below 150 m, but ranges up to 600 m where mountains occur adjacent to the ocean (Franklin and Dyrness, 1973). The extent of this forest zone is controlled by prevailing climatic conditions outlined in Franklin and Dyrness (1973) and is characterized by (1) mild, wet climate, (2) minimal annual extremes in temperatures and precipitation, and (3) frequent fog and low clouds during the relatively drier summer months. Quinault, Wash., and Port Orford, Oreg., are both in the Picea sitchensis zone, and the difference between average temperatures for January and July is 13.5°C at Quinault and 7°C at Port Orford. Annual precipitation averages 2 to 3 m, with an average of 25 cm of rain in Quinault, and 8 cm in Port Orford during the period June-August. During the summer, fog drip provides additional moisture as a consequence of condensation in tree crowns. The presence of significant amounts of Picea pollen at the 44- and 43-m levels (pl. 12, 13; table 3) indicates similar climatic conditions once existed in the vicinity of Bolinas, approximately 150 km south of the present southernmost viable natural stands of P. sitchensis.

No comparable record of Picea was found in cores from Clear Lake, Calif., located 120 km north of Bolinas Lagoon, although the record recovered there extends back as far as Sangamon (David P. Adam, oral commun., 1977). One explanation for this may be that although increased rainfall may have occurred at Clear Lake, the mitigating effects of summer fog were absent there, thus making that area inhospitable for Picea. The west shore of Clear Lake is approximately 60 km inland from the present strand of the Pacific Ocean, and a Late Pleistocene-Early Holocene P. Sitchensis zone comparable to the extant zone would probably have extended along a narrow coastal strip, tens of kilometers west of the lake.

No radiocarabon dates have yet been obtained on peaty material from the 44- and 43-m levels, which would date the Picea at Bolinas Lagoon. The disappearance of Picea pollen between the 43- and 41-m levels in borehole 4 very likely corresponds to a change in climate characterized by warmer conditions. The fossil pollen and radiocarbon dates from Clear Lake indicate that a warming trend began at approximately 13,000 years B.P. (David P. Adam, oral commun., 1977), and this period of warming may correspond in part to the 43- to 41-m segment of borehole 4 at Bolinas. A radiocarbon date of 8,400±100 years B.P. was obtained on reddish-brown, fibrous, peaty material from the 38-m level lending credence to the possibility of a 13,000-years-B.P. age for some point in the 43- to 41-m segment.

Implications of other pollen

A wet or moist climate for the 44- to 41(?)-m segment is evidenced by other fossil pollen as well. Salix (willow) comprises 4 to 5 percent of the total pollen in the 44- and 43-m levels and declines in abundance up to the 35-m level, above which it disappears from the record. Several species of Salix now inhabit the Pacific coastal area, and all of them typically prefer moist to wet habitats, commonly along stream channels (Munz and Keck, 1973). The upward decline in abundance of Salix (pl. 12, 13) may indicate a drying environment.

The freshwater alga Pediastrum, which is found at the 43- and 41-m levels, requires some open water (Adam, 1975), and generally occurs in small lakes or ponds (Hutchinson, 1967). Pollen from sediments in Potato Lake, Ariz., indicate a maximum occurrence of P. boryanum during pluvial times (Whiteside, 1965) and this may also be the case at Bolinas, as indicated by the association of Picea and Pediastrum at the 44- to 43-m levels. Another alga, Botryococcus, was found at the 43-m level, and occurs in either fresh or brackish water (Adam, 1975).

Isoetes (Quillwort), found in the 44- to 38-m levels, includes aquatic, amphibious and terrestial species, and typically occurs in or near ponds or lakes (Munz and Keck, 1973). Myrica (wax-myrtle and sweet gale) occurs from the 44- to 38-m levels, and also inhabits moist areas (Abrams, 1923; Munz and Keck, 1973).

Pteridium (bracken) and Botrychium (grape fern) also are typically found in moist or damp places (Munz and Keck, 1973), and in conjunction with other flora from the lowest three levels indicate a moist or wet environment.

Relatively high percentages of Cyperaceae (sedge family), 16 to 33 percent in the 44- to 41-m core segment, imply relatively wet conditions. Pollen profiles from British Columbia indicate abundant Cyperaceae in late-glacial and early-post-glacial sediments with a subsequent decline during the hypsithermal, indicating the moderately high moisture requirements of this family (Heusser, 1960). Other cores from California also indicate that Cyperaceae was more abundant during the Late Postglacial under the cooler, more humid climate (Heusser, 1960). At the 38-m level of borehole 4, the percentage of Cyperaceae is reduced to only 2 percent of the total pollen and implies warmer, drier conditions or perhaps seasonally dry conditions.

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Arceuthobium, one genus of the mistletoe family, is parasitic only on conifers (Munz and Keck, 1973) including species of Abies (fir), Larix (larch), Pinus (pine), Pseudotsuga (Douglas fir) and Tsuga (hemlock), but not Sequoia (redwood) (Abrams, 1923). Arceuthobium comprises up to 1 percent of total pollen in the lowest three levels of borehole 4 from 44 to 41 m. Above 41 m it disappears from the record, and implies a reduction in the abundance of host conifers. Above 41 m, there is a decrease in Pinus (pine), although there is a corresponding rise in TCT pollen, which primarily includes S. sempervirens. At 35 m, Pinus continues to diminish, but the deciduous trees Acer (maple) and Alnus (alder) increases in abundance. The percentage of Quercus (oak) is variable, but generally increases upward in the core. This pattern suggests a change in the character of the upland forest from primarily conifer to mixed conifer/angiosperm.

The TCT curve shows increasing abundance above the 41-m level. The increase may be due to (1) landward movement of the coastal S. sempervirens belt in response to rising sea level and landward migration of the strand line, (2) geographic spread of this species or (3) the possibility of decomposition of redwood pollen at depth (Heusser, 1960), and because of this, no climatic significance is attached to this trend.

A peak in abundance of Cheno-am pollen occurs at 38 m and corresponds to a marked decrease in Cyperaceae at that level. Whereas abundant Cyperaceae pollen indicates moist or wet conditions, the influx of Cheno-ams may indicate fluctuating environmental conditions. Cheno-ams may be among the first plants to inhabit the receding shore of a seasonally drying lake or pond; therefore, the rise of Cheno-am pollen at 38 m may signify drying conditions or repeated drying conditions (David P. Adam, oral commun., 1977). Chenopodiaceae have been used as indicators of a brackish-water environment in cores from Devil's Lake, Oreg. (Heusser, 1960), and this interpretation is consistent with repeated drying of a lake or pond indicated at the 38-m level of borehole 4.

Because Cyperaceae pollen constitutes a relatively high percentage of total pollen for the lowest three levels, it might have affected the shape of other pollen curves, inordinately depressing them and resulting in misleading analysis of changes in vertical pollen distribution. Plate 13 is plotted so that the total pollen for each level adds up to a fixed sum (100 percent); hence, if one variable increases in relative frequency, some other variable(s) must decrease, and this constraint causes positively correlated or independent variables to appear negatively correlated (Adam, 1967). To determine whether the high percentage of Cyperaceae pollen at the 44-, 43-, and 41-m levels greatly affected the curve geometry for Cheno-am and Pinus (pine) pollen, the Cyperaceae were subtracted from the totals, percentages recalculated, and the curves replotted as dashed lines on plate 13. In each case, the curves are shifted only slightly, indicating real increases in Cheno-am pollen from the 44- to 38-m level, and a real decrease in Pinus pollen at the 43-m level. Because the curves are only minimally shifted by the presence of large amounts of Cyperaceae, the interpretations of environments on the basis of upward changes in the Cheno-am and Cyperaceae curves are assumed to be unaffected.

Typha is only found at the 38-m level, in association with a relatively high percentage of Cheno-am pollen (13 percent). Typha is a freshwater-marsh or aquatic plant (Abrams, 1923; Munz and Keck, 1973) and is commonly found in association with several species of the Cyperaceae family in freshwater marshes near the coast (Heusser, 1960). Thus, the presence of Typha may indicate freshwater-marsh conditions at the 38-m level, and is consistent with the interpretation of an environment generally drier than that inferred for levels below 38 m. Reduction of a pond or lake to a marshy area, or repeated filling and drying, might produce the changes indicated by the pollen curves. Increasing amounts of Cheno-am and decreasing amounts of Cyperaceae pollen in a core taken from Elkhorn Slough, Calif., were interpreted by Mudie (unpub. data, 1975) to indicate reduced freshwater influence.

Ostrea lurida (native Pacific oyster) is a marine pelecypod commonly found in the intertidal or low intertidal zone in places with a hard or rocky substrate (Ricketts and Calvin, 1968; Keen and Coan, 1974). Its presence at the 35-m level indicates marine transgression below this level. The terrestrial/marine boundary may be indicated by the change in sediment character from clayey silt to clayey, silty sand at about the 35.5-m level (pl. 10). The fluctuating character of the sediments between 35.5 m and 34 m may signify an interfingering of marine and terrestrial sediments within this interval.

The presence of 3 percent Triglochin (arrow-grass) in the 35- and 27.5-m levels indicates nearby marshes. T. maritima, T. striata, and T. concinna are presently found in coastal salt marshes in California (Munz and Keck, 1973) and are probably represented in the Triglochin curve above the 38-m level. The presence of Triglochin pollen was used by Mudie (unpub. data, 1975) to indicate tidal inundation. The Triglochin pollen below the 38-m level probably comes from species different from those above the 38-m level because of (1) the Triglochin hiatus between the 41- and 35-m levels, and (2) the apparent environmental change from freshwater to marine conditions.

Summary and conclusions

The pollen profiles for the 44- to 27.5-m segment of borehole 4 indicate significant changes in both local environment and regional climate. The evidence from the 44- to 43-m levels, and to a lesser extent, the 41-m level indicates a cool, moist to wet climate with minimal annual extremes in temperature and precipitation, and frequent fog and low clouds during summer months.

Changes in the character of the upland forest include (1) elimination of Picea above the 43-m level, (2) a decline in total Pinus pollen between the 41- and 35-m levels, (3) an inferred decline in conifers above the 41-m level as evidenced by the disappearance of _Arceuthobium_, and (4) an increasing proportion of angiosperm trees above the 41-m level.

NAP profiles suggest that sediment from the 44- to 41-m levels accumulated in a freshwater lake or pond. Above the 41-m level, increasing abundance of Cheno-am pollen, a decrease in Cyperaceae, and the appearance of _Typha_ suggest a change to significantly drier conditions. Pollen from the 38-m level may indicate a freshwater marsh, or possibly a small lake or pond that alternately (seasonally?) filled and dried.

The 35-m level is marine, as evidenced by the presence of _Ostrea lurida_ indicating a marine transgression between the 38- and 35-m levels. From 35 to 27.5 m, NAP indicate that sediments accumulated in or near a salt marsh or other shallow near-shore environment. The record from 44 to 27.5 m indicates a transgressive sequence.

EFFECTS OF LOGGING ON SEDIMENTATION IN THE UPPER BASIN OF BOLINAS LAGOON

Previous estimates of rates of sediment accumulation in Bolinas Lagoon have generally been calculated for long-term periods. Helley (1969) utilized rates of erosional retreat of the Bolinas cliffs (fig. 14) in estimating volumes of material transported into the lagoon. Wahrhaftig (1970) estimated average rates of sediment accumulation of 7.5 to 30 cm/100 years based upon inferred profiles of the pre-lagoon valley. Rowntree (1973) used depths inferred from a seismic reflection survey to calcualte an average long-term sediment accumulation rate of 40 cm/100 years, and he compared 1939 and 1968 bathymetric surveys of the lagoon to calculate a rate of 45 cm/100 years.

Sediment accumulation in Bolinas Lagoon became a matter of concern in the 1850's, when nearby logging apparently accelerated erosion in the watershed and caused increased sedimentation in the lagoon. Redwood logging began near Bolinas Lagoon in 1849. Initially, cut logs were taken to the head of the lagoon and rafted through the inlet to ships that took them to San Francisco. After construction of the first sawmill in 1851, logs were taken by oxcart to mills for cutting into lumber, which was then transported to the head of the lagoon where it was loaded onto lighters. The last of the sawmills was constructed in 1858, but operated only a short time. An estimated 13 to 15 million board feet of lumber were cut in the vicinity of Bolinas before large-scale logging ceased shortly after 1858 (Munro-Fraser, 1880).

Today the only visible remains of 19th-century logging are tree stumps and the pilings from a lighter wharf (fig. 11) constructed in the mid-1850's for the lighters that transported lumber to ships anchored outside the lagoon.

Effects of logging

The effects of 19th-century logging are assumed to be similar to those observed today. Several recent studies demonstrate the relationship between logging and subsequently accelerated erosion and sedimentation (Janda, and others, 1975; Megahan, 1976; Megahan and Kidd, 1972).

Megahan (1976) describes erosional processes and the changes effected on them by logging. Increasing surface erosion, the movement of individual soil particles over the ground, results not just from timber cutting, but from activities associated with logging that (1) destroy ground cover, (2) disrupt soil structure, (3) increase raindrop impact, and (4) decrease soil infiltration rates enough to cause surficial water flow. These effects are especially severe on roads; and road construction may accelerate erosion by (1) increasing slope gradients through cut and fill, (2) intercepting subsurface water flow, and (3) concentrating surface water flow on the road and asssociated channels (Megahan, 1976). A study in Idaho by Megahan and Kidd (1972) indicates that in logged areas disturbed by roads, surface erosion per unit area increased an average of 220 times that in nearby undisturbed land. Watershed disturbances from logging can also cause landslides in areas of (1) relatively steep slopes, (2) shallow soils, and (3) rapid, large volume water input (Megahan, 1976). Prior to logging, forest areas are stabilized by deeply rooted vegetation. After logging, tree roots eventually rot, resulting in decreased soil stability and increased potential for landslides. Landsliding moves soil and rock downslope into stream channels, further disrupts vegetal ground cover, and leaves exposed soil susceptible to erosion (Janda, 1976).

Core location

Core 6-76 was taken in the Upper Basin of Bolinas Lagoon approximately 1 km north of Pine Gulch Creek, the closest perennial stream (fig. 20). This is a quiet water area in which very fine grained sediments are deposited and was selected as a coring site because: (1) the most reliable pollen records are generally obtained from very fine grained, low-energy environments, hence a short core will sample more "time" than one taken in areas of higher sedimentation, (2) rates of sediment accumulation in this area are probably among the lowest in the lagoon, and projections based upon these figures will therefore be conservative, and (3) the Upper Basin is likely to be sensitive to major shifts in patterns of erosion and sedimentation within the Bolinas Lagoon drainage basin.

Sampling and analysis

The core was taken using a section of 7.6-cm-diameter, clear plastic pipe, which was pushed into the sediment by hand and extracted using a portable A-frame support. A flanged rubber stopper that fits inside the pipe maintains a vacuum to prevent core loss during extraction. The core was split longitudinally, half for sediment analysis and half for pollen analysis.

Pollen extraction involved the use of standard techniques described by Faegri and Iversen (1975). To each 2.6 cm^3 sample, a known quantity of *Lycopodium* spores (25 ± 1K) was added as a tracer before processing to enable calculation of absolute pollen concentrations (Stockmarr, 1971). Processing included the following treatments: (1) 10 percent HCl, (2) 10 percent KOH, (3) 48 percent HF, (4) concentrated HNO_3, and (5) acetolysis. Residues were stained with safranin and stored in 200 centistokes viscosity silicone oil. High clay concentrations were initially problematic, but this was overcome by repeated washings after the KOH treatment and by centrifuging for 1 minute at 2,000 rpm. Counting was done at 400 X magnification on a Leitz Dialux microscope with a planachromat objective. Counts of at least 200 grains per sample were made and are listed in table 5 as grains per cm^3. As a precaution against bias, counts were made on coded slides.

Sedimentary analysis was done by two methods including (1) standard sieving techniques for grain sizes 3.5 phi (0.0880 mm) and larger, and (2) hydrophotometer analysis of grain sizes smaller than 3.5 phi. A Technical Systems Services (TSS) Model 7312 hydrophotometer was used to make timed measurements of the decreasing occlusion of a beam of light transmitted through a tube containing a small amount of sample shaken and suspended in water. Sieve weights and hydrophotometer readings were analyzed with a computer program that calculated grain-size parameters including (1) moments, (2) mean, (3) median, (4) sorting, (5) skewness, (6) kurtosis, (7) percent of total sample wight for grain sizes at half phi intervals, (8) cumulative percents, and (9) percentages of gravel, sand, silt and clay, and ratios of these size classes (table 4).

Plate 14 presents a graphical summary of sediment and pollen analyses, and the numerical values of plotted points are listed in table 4 for sediments and table 5 for pollen.

The first moment is the mean and is a measure of the average grain size of the sample. The square root of the second moment is the standard deviation (σ) or sorting and is a measure of the spread of the frequency distribution curve from the mean. The third moment (or approximately its cube root) is a measure of skewness or asymmetry of the frequency distribution curve. The fourth moment (or approximately its fourth root) is a measure of kurtosis or peakedness of the frequency distribution curve (append. A).

Pollen markers

In order to utilize pollen types as chronological markers for dating sediments and calculating rates of sediment accumulation, it is necessary to have (1) alien pollen types with known dates of introduction, or (2) native pollen types with known dates of increasing or declining abundance. Three plant species not indigenous to North America have been introduced into the Bolinas area, and their pollen can be readily identified. The three plants, in ascending chronological order of introduction, are *Rumex acetosella*, *plantago lanceolata*, and *Eucalyptus* sp. Prior to this study, the dates of introduction of the first two were known only generally. However, *Eucalyptus* has a well-documented time of arrival in California.

The genus *Eucalyptus* consists of more than 150 species of evergreen angiosperms native to Australia and nearby islands. *Eucalyptus* was first introduced into North America in January 1856, when 14 species were successfully planted in California by a resident of San Francisco (Kinney 1895; McClatchie, 1902). The trees were first planted as ornamentals, but by 1870 had gained widespread use as utility plantings. Their ability to grow easily and quickly and the hardness of their wood made them useful for shade, fuel, and windbreaks.

Table 4.--*Grain size parameters for core 6-76*

Depth Below Surface (cm)	Moments ϕ				Sediment ratios						Sediment size percentages			
	M_1	M_2	M_3	M_4	Gravel/Sand	Sand/Silt	Silt/Clay	Sand/Clay	Sand/Mud[1]	Gravel/Mud[1]	Gravel	Sand	Silt	Clay
0	5.93	2.13	0.23	0.15	*	0.213	7.999	1.703	0.19	*	*	15.92	74.74	9.34
10	5.94	2.00	0.12	0.74	*	0.128	10.382	1.332	0.12	*	*	10.45	81.45	7.85
20	5.00	2.02	0.52	0.77	*	0.585	9.809	5.735	0.53	*	*	34.66	59.29	6.04
30	6.93	2.09	0.37	-0.20	*	0.035	3.817	0.134	0.03	*	*	2.72	77.09	20.20
40	6.61	2.60	0.20	-0.51	*	0.328	2.445	0.801	0.23	*	*	18.87	57.58	23.55
50	5.93	2.63	0.23	-0.23	*	0.476	3.340	1.591	0.37	*	*	26.73	56.14	16.81
60	4.81	2.68	0.44	0.12	0.021	1.421	3.128	4.446	1.08	.023	1.07	51.30	36.09	11.54
70	4.97	2.78	0.32	-0.03	0.011	1.228	3.089	3.795	0.93	.010	0.53	47.88	38.98	12.62
85	5.48	2.48	0.39	-0.02	0.001	0.655	4.135	2.707	0.53	.001	0.05	34.50	52.71	12.75
95	4.51	2.20	0.68	0.28	0.001	1.789	5.444	9.739	1.51	.002	0.07	60.14	33.61	6.18
105	5.13	2.67	0.25	-0.17	0.007	1.004	4.406	4.423	0.82	.006	0.32	44.85	44.68	10.14
110	5.06	2.76	0.33	-0.06	0.008	0.990	3.374	3.340	0.76	.006	0.34	43.15	43.59	12.92
115	6.03	2.49	0.35	-0.21	*	0.362	3.564	1.290	0.28	*	*	22.04	60.88	17.07
120	6.09	2.63	0.18	-0.13	*	0.332	3.356	1.114	0.26	*	*	20.16	60.76	18.10
130	6.21	1.94	0.33	0.30	*	0.144	8.029	1.158	0.13	*	*	11.37	78.82	9.82
140	6.64	2.31	0.28	-0.33	*	0.161	3.608	0.583	0.13	*	*	11.23	69.51	19.27
150	6.24	2.21	0.49	-0.02	*	0.103	4.721	0.484	0.09	*	*	7.80	76.08	16.12
160	5.62	2.18	0.60	0.39	*	0.277	5.722	1.582	0.24	*	*	19.06	68.90	12.04
170	5.87	2.30	0.38	0.11	*	0.290	5.044	1.463	0.24	*	*	19.45	67.06	13.30
180	5.39	2.36	0.41	0.26	0.004	0.424	5.621	2.382	0.36	.002	0.11	26.43	62.37	11.10
188	5.72	2.42	0.27	0.09	*	0.331	5.104	1.690	0.28	*	*	21.69	65.48	12.83

[1] Mud includes silt and clay

Eucalyptus is insect-pollinated, and large volumes of wind-disseminated pollen are not produced. Thus, Eucalyptus must be near a given core site in order to produce a statistically reliable pollen record. The introduction of Eucalyptus into California in 1856 therefore does not imply ubiquity of pollen at that time. The date of local introduction of Eucalyptus rather than the date of initial North American introduction provides the maximum age for the Eucalyptus pollen datum in a given area.

According to Thomas Barfield, Esq., a historian of Bolinas (oral commun., 1976), the first Eucalyptus near Bolinas Lagoon were planted in the early 1870's. These first trees, E. globulus, were planted north of the lagoon as windbreaks, and some are still standing. Verification of the age of these trees by coring and counting growth rings is not feasible because the yearly growth rings of Eucalyptus are characteristically indistinct.

Rapid growth is characteristic of many species of Eucalyptus, and McClatchie (1902) calls E. globulus, the Blue Gum, the fastest growing tree in the world, citing examples of their attaining heights of 15 to 23 m in 5 to 10 years.

In addition to rapid growth rates, Eucalyptus characteristically produce flowers early in their development, and with favorable conditions, flowers can develop on trees only 2 or 3 years old (McClatchie, 1902). The equable, temperate climate of the Bolinas area fulfills all requirements for vigorous growth, and it is therefore not unlikely that the trees planted in the 1870's flowered early. Adding the time of maturation of the trees, 2 to 3 years, to the date of planting, 1871-73(?), yields a maximum date of about 1875 for the first production of Eucalyptus pollen in the vicinity of Bolinas Lagoon. Assuming a later planting and delayed flowering, 1880 would then probably represent a conservative date for the first introduction of Eucalyptus pollen in this area.

The dates for the introduction of both European weeds, Rumex acetosella (sheep sorrel) and Plantago lanceolata (ribwort, English plantain or buckhorn plantain), into both California and the vicinity of Bolinas Lagoon are less certain. The uncertainty arises from incompleteness of late 18th and 19th-century botanical records. Specimens were rarely collected systematically, and the local appearance of alien plants was likewise rarely noted. A complicating factor is that the spread of introduced species is not instantaneous, so that the first recorded occurrence of a particular species in California does not necessarily imply ubiquity. For places where there are no specific records of either introduction or early presence of these plants, the determination of the dates of introduction must be inferred from local cultural history in conjunction with documented occurrences of these plants in other areas. In this way, time span within which the plants were likely to have been introduced can be determined.

Analysis of plant remains in adobe bricks from Rancho Natividad near Monterey by Hendry and Kelly (1925) indicates the presence of sheep sorrel, Rumex sp. and raises the possibility that Rumex acetosella had been introduced in the Monterey area by 1837.

Plantago lanceolata from fields near San Francisco was included in the botanic collection of the Geological Survey of California in 1860-1864, and a notation states: "The Ribgrass, Ripplegrass, or English plantain; introduced from Europe; apparently not widely established" (Brewer and others, 1876). In a subsequent report pertaining to the same botanic collection, it is noted that Rumex acetosella is "a very widely-spread weed from Europe, the common 'sorrel' of fields and gardens, spreading rapidly in light soils by its slender running rootstocks" (Watson, 1880).

These reports indicate that by 1860-1864 Rumex acetosella was well established in parts of California, whereas the extent of Plantago lanceolata was limited. From this it may be inferred that R. acetosella was introduced prior to P. lanceolata. Frenkel (1970) lists Rumex acetosella as introduced into California within the period 1825-48 and Plantago lanceolata as introduced during the period of American settlement, 1849-60.

Calculated dates of pollen introduction and sources of uncertainty

Dates of introduction of both Plantago lanceolata and Rumex acetosella in the vicinity of Bolinas Lagoon can be determined by utilizing calculated rates of sediment accumulation, discussed below, in conjunction with dated core horizons. The first occurrence of P. lanceolata is at the 80-cm core level, above the onset of redwood logging (pl. 14; see also discussion below) and below the first occurrence of Eucalyptus pollen at the 70-cm level. P. lanceolata was therefore introduced during the 1849 to 1875-80 period. By using sediment accumulation rates for this period of 1.3 to 1.7 cm/yr and dividing into distances from the 115- to 70-cm levels, a date of approximately 1868-73 is established for the introduction of Plantago lanceolata into the Bolinas area. If sediment accumulation rates decreased from 1849 to 1875-80, then the date of introduction would be older; conversely, if the accumulation rates increased, the date would be younger. The former possibility is more likely because large-scale logging ceased by 1860, and the watershed disturbances resulting from logging probably moderated after its cessation.

Rumex acetosella was first encountered at the 100-cm level. By applying similar methods of calculation, Rumex acetosella is determined to have been established in the Bolinas area between 1857 and 1859.

Uncertainties in using pollen for dating sediments have two principal causes: (1) contamination of samples during sampling or pollen separation, and (2) bioturbation. Contamination of samples can generally be avoided by careful field and laboratory methods, but the effects of bioturbation are difficult to avoid, especially in marine and estuarine deposits because burrowing animals can move pollen up or down in a section.

Broken bivalve fragments were found in nearly every level of core 6-76, and many of these were identifiable as Macoma nasuta, the "bentnosed clam," a common inhabitant of tidal flats and quiet, shallow water along the west coast of North America from Alaska to Baja California. Macoma is a burrowing animal, which usually resides at depths of less than 15 cm, although Addicott (1952) reports that large individuals 4 to 5 cm long may be found as deep as 25 cm below the surface. Most of the fragments in core 6-76 appear to be from small bivalves less than 3-cm long, and therefore the maximum depth of bioturbation is probably 15 cm or less. The largest Macoma nasuta valve in the core, 4 cm long, was found at the 138 cm level. Its maximum burrowing depth was thus perhaps as much as 25 cm; however, the depth at which it was found is well below the first appearance of any of the three introduced pollen types. The size and abundance of bivalve fragments sharply decreases above the 115-cm core level, and the quantity of fragments remains low up to the 50-cm level, at which point bivalves again become abundant. Only occasional small bivalve fragments were found in the 105-to 70-cm core segment. The bivalve-minimum zone in the core (115-50 cm) coincides with sediments deposited during the period affected by redwood logging as determined from sedimentary analysis, and it appears that the decrease in bivalve abundance correlates with increased rates of sediment accumulation. The bivalve-minimum zone implies a minimum of vertical pollen movement resulting from bioturbation. Because the critical first appearances of the three alien pollen types are within the bivalve-minimum zone, it is assumed that the positions of the first appearances in the core were not materially affected by bioturbation. If, however, Eucalyptus pollen was moved down in the core through bioturbation, rates of sediment accumulation for the 1849 to 1875-80 period (115-110 to 70 cm) would be greater, and rates for the 1875-80 to 1906 period (70 to 30-20 cm) would be less than those shown in table 6.

Interpretation of changes in grain-size parameters and pollen frequencies

The lowest and stratigraphically oldest levels of core 6-76, from 188 to 130 cm, are similar in sedimentary character, with only minor fluctuations in mean grain size and skewness (pl. 14), and are interpreted as representative of the presettlement period in this area. Pollen concentrations in this segment of the core, particularly Pinus and TCT, are more variable, probably reflecting relatively low total counts rather than ecologic changes. The absence of alien pollen types also indicates that these sediments predate European settlement at Bolinas.

Mean grain size increases slightly from 130 to 120 cm; in addition degree of sorting becomes significantly less and skewness and kurtosis values decrease (pl. 14). The shift in this part of the core toward a less positively skewed distribution indicates the addition of a coarse fraction to a predominately fine-grained sediment. Above this, in the 120- to 115-cm core segment, there is a short interval in which mean grain size remains nearly constant, degree of sorting improves slightly, and skewness becomes more positive. The 130- to 115-core segment is interpreted as a time of alteration of preexisting conditions of sedimentation; it is inferred that variations in mean grain size and other grain-size parameters reflect increasing rates of erosion perhaps resulting from man's activities west of the lagoon about 1835-40.

115-50 cm

Sediments between 115 and 110 cm display major changes in grain size parameters with gravel/sand ratios, sand/mud ratios, and mean grain size increasing sharply and degree of sorting becoming poorer. In addition, there is a color change in sediments from dark gray to dark olive gray that corresponds to increasing amounts of fibrous and woody plant debris. Above the 115-cm level the number of bivalve fragments decreases, possibly in response to changing conditions of sedimentation in the lagoon. The changes in grain-size parameters and the changing character of organic constituents are interpreted as resulting from initiation of nearby redwood logging in 1849.

At the 115- to 110-cm core levels, the pollen curves for pine (*Pinus*), oak (*Quercus*), alder (*Alnus*), Cheno-am and TCT indicate sharply decreasing abundance (pl. 14). The primary reasons for decreasing abundance of pollen types above 115 cm, in the core segment affected by logging, are a decrease in pollen rain because of plant destruction, and the dilution of the number of pollen grains per cm^3 of sediment resulting from increased rates of sediment accumulation. These two reasons for measured decreases in pollen abundance are additive phenomena and thereby accentuate pollen minima.

The 110- to 50-cm core segment approximately defines the pollen-minimum zones (pl. 14) for TCT, as well as for pine, oak, and alder, trees that were extensively cut for cordwood and lumber in the years between 1850 and 1880. Munro-Fraser (1880) indicates that pine, oak, and alder were formerly abundant, but that by 1880 "the major portion has long since been chopped out." The pollen-minimum zones for these trees thus probably also reflect their depletion by logging activity. On the basis of pollen concentrations, redwoods apparently never reestablished to prelogging levels of abundance. Oak and alder, however, appear to become more abundant in the top 30 cm than prior to logging, indicating the possibility of ecologic replacement of redwood.

The Cheno-ams, which include numerous salt-marsh plants, rain pollen almost directly into the lagoon and have a pollen-minimum zone in the 110- to 50-cm core segment, possibly indicating marsh destruction around the northern perimeter of the lagoon due to construction of roads and wharves, and sledding of logs into the lagoon.

Redwood(?) fragments 1-4 mm long are common from 105 to 70 cm. A wood fragment, 6.5 mm long from the 105-cm core level, had two parallel cross-grain cuts suggesting an ax or saw chip. SEM photographs of wood from the 105- to 110-cm levels revealed structure indicating that it was not from deciduous trees. Identification of genus was not possible though because of the deteriorated condition of the wood fragments (David P. Adam, oral commun., 1977).

In the 115- to 50-cm core segment, there is an approximate correlation of (1) the bivalve-minimum zone, (2) pollen minimum zones for pine, oak, alder, Cheno-am, and TCT, (3) abundant woody debris, and (4) sediments which, relative to core segments above and below, are generally characterized by larger mean grain size, poorer sorting, and high gravel/sand and sand/mud ratios. At approximately the 50-cm level, (1) bivalves again become as abundant as in pre-logging period sediments, (2) pollen concentrations increase, (3) woody fragments become scarce, and (4) sediments become finer grained, better sorted, with lower gravel/sand and sand/mud ratios. These changes indicate decreased erosion of the watershed resulting in lower sediment accumulation rates in the lagoon. Decreasing rates of sediment accumulation result in increasing pollen concentration, all other factors being the same, although part of the rise in pollen concentration may reflect increased pollen rain due to renewed abundance of certain plants, for example the reestablishment of salt-marsh plants at the north end of the lagoon. Increasing bivalve abundance at 50 cm may also indicate decreased sediment accumulation rates. Changes in bivalves, pollen, wood, and mean grain size at 50 cm are interpreted as probable indications of the diminishing effects of watershed disturbances caused by logging.

50 cm to surface and possible sedimentary record of 1906 earthquake

The changes in sedimentary character noted at the 50-cm level generally persist to the top of the core with one clear exception at the 20-cm level, which may be a sedimentary signature of the 1906 earthquake. Sediments above the 50-cm level, when compared with those in the 115- to 50-cm core segment, are characterized by (1) smaller mean grain size, (2) better sorting, (3) lower positive skewness, and (4) lower gravel/sand and sand/mud ratios (pl. 14). At the 20-cm core level, there is a sedimentary anomaly characterized by (1) larger mean grain size, (2) high positive skewness, and (3) higher sand/mud ratio, and indicates a brief influx of larger particles. This short-lived perturbation of fine-grained sediment accumulation may result from the 1906 earthquake.

Gilbert (1908) measured a 30-cm downdrop of Bolinas Lagoon between the 1906 trace of the San Andreas fault and the eastern shore, based upon (1) plant mortality caused by increased duration of tidal submergence in the lowest 30 cm of *Salicornia* marshes, (2) more frequent overtopping of the spit by waves, and (3) reports of improved navigability in the lagoon near McKennan Island. Lagoonal downdrop of 30 cm probably would increase stream gradients at the point where they crossed the fault and would cause transport of coarser grained particles into areas of the lagoon that previously received only fine-grained sediments. The transport of coarse material would dissipate as streams and downdropped margins reestablished equilibrium. Another factor probably affecting sedimentation in the lagoon following the 1906 earthquake was increased erosion due to ground breakage and landslides. This may have resulted in a temporary increase in the amount of sediment transported into the lagoon and a short-term increase in rates of sediment accumulation. Gilbert (1908) indicates landslides blocked the road near the point where the fault trace leaves the lagoon near the site of core 6-76 (fig. 20, plate 5) and it is also possible that slide debris washed directly into the lagoon resulting in the anomalous coarse-grained sediment at the 20 cm core level. In any case, the sedimentary event recorded at 20 cm may correlate with the 1906 earthquake and provide a "time" horizon which can be utilized in estimating rates of sediment accumulation.

Pollen concentrations are nearly constant for the top 30 cm, and show no changes that might indicate effects of the 1906 earthquake. Cheno-am pollen concentrations, which might have declined due to *Salicornia* mortality, showed only a very small decrease (table 5) probably because only slight marsh destruction occurred in the north end of the lagoon.

Pollen concentrations of *Gramineae* (grasses) and *P. lanceolata* drop sharply in the top 30 cm (pl. 14) and may reflect changing land use. A corresponding rise in the *Quercus* (oak) pollen concentrations above 30 cm suggests that succession may have occurred following reduced cattle grazing in the hills around the lagoon (Roger Byrne, oral commun., 1977).

Graphical summary of changes in core sediments

A graphical summary of grain-size changes in core 6-76 is shown in figure 25. The sudden shift in grain-size percentages between the 115- and 110-cm core levels is interpreted as resulting from the inception of large-scale redwood logging around Bolinas Lagoon in 1849. From 115 to 110 cm, the percentage of sand nearly doubles and percentages of both silt and clay decrease by almost one-third, indicating a major shift in sedimentation patterns. Samples from 110 to 60 cm are clustered in an area of the graph characterized by relatively high percentages of sand and correspondingly low percentages of silt and clay. The 50-cm level shows a return to finer grained sediments similar to prelogging period sediments at 115 and 120 cm. Above 50 cm, the sediments become

Table 5.--*Core 6-76 pollen concentrations, in tens of grains per* cm^3

Depth below surface (cm)	Eucalyptus	Plantago lanceolata	Rumex acetosella	Cheno/Am	TCT	Gramineae	Alnus	Quercus	Pinus
0	58.3	108.3	41.7	58.3	116.7	116.7	300.0	183.3	83.3
10	41.7	183.3	25.0	125.0	233.3	233.3	208.3	191.7	108.3
20	40.0	290.0	10.0	90.0	80.0	300.0	470.0	200.0	60.0
30	18.2	181.8	36.4	90.9	172.7	390.9	372.7	54.5	63.6
40	14.3	78.6	28.6	64.3	178.6	178.6	192.9	78.6	150.0
50	17.6	70.6	23.5	94.1	135.3	200.0	223.5	52.9	35.3
60	3.8	30.8	26.9	38.5	88.5	73.1	142.3	50.0	23.1
70	3.7	*	74.1	22.2	81.5	66.7	48.1	29.6	37.0
80	*	4.3	65.2	39.1	108.7	34.8	73.9	34.8	56.5
85	*	*	61.1	33.3	138.9	111.1	77.8	50.0	27.8
90	*	*	3.3	43.3	96.7	33.3	60.0	50.0	40.0
95	*	*	13.6	31.8	86.4	172.7	54.5	36.4	45.5
100	*	*	6.5	122.6	174.2	87.1	151.6	67.7	67.7
105	*	*	*	136.4	150.0	40.9	100.0	45.5	86.4
110	*	*	*	84.4	131.2	28.1	184.4	34.4	118.7
115	*	*	*	220.0	206.7	80.0	166.7	40.0	113.3
120	*	*	*	214.3	164.3	100.0	257.1	42.9	171.4
130	*	*	*	215.4	223.1	53.8	215.4	92.3	146.2
140	*	*	*	164.3	192.9	107.1	200.0	57.1	185.7
150	*	*	*	168.7	293.7	37.5	181.2	93.7	118.7
160	*	*	*	206.2	275.0	75.0	187.5	81.2	68.7
170	*	*	*	228.6	207.1	185.7	271.4	64.3	92.9
180	*	*	*	173.3	200.0	66.7	146.7	73.3	93.3
185	*	*	*	250.0	137.5	106.2	118.7	68.7	106.2

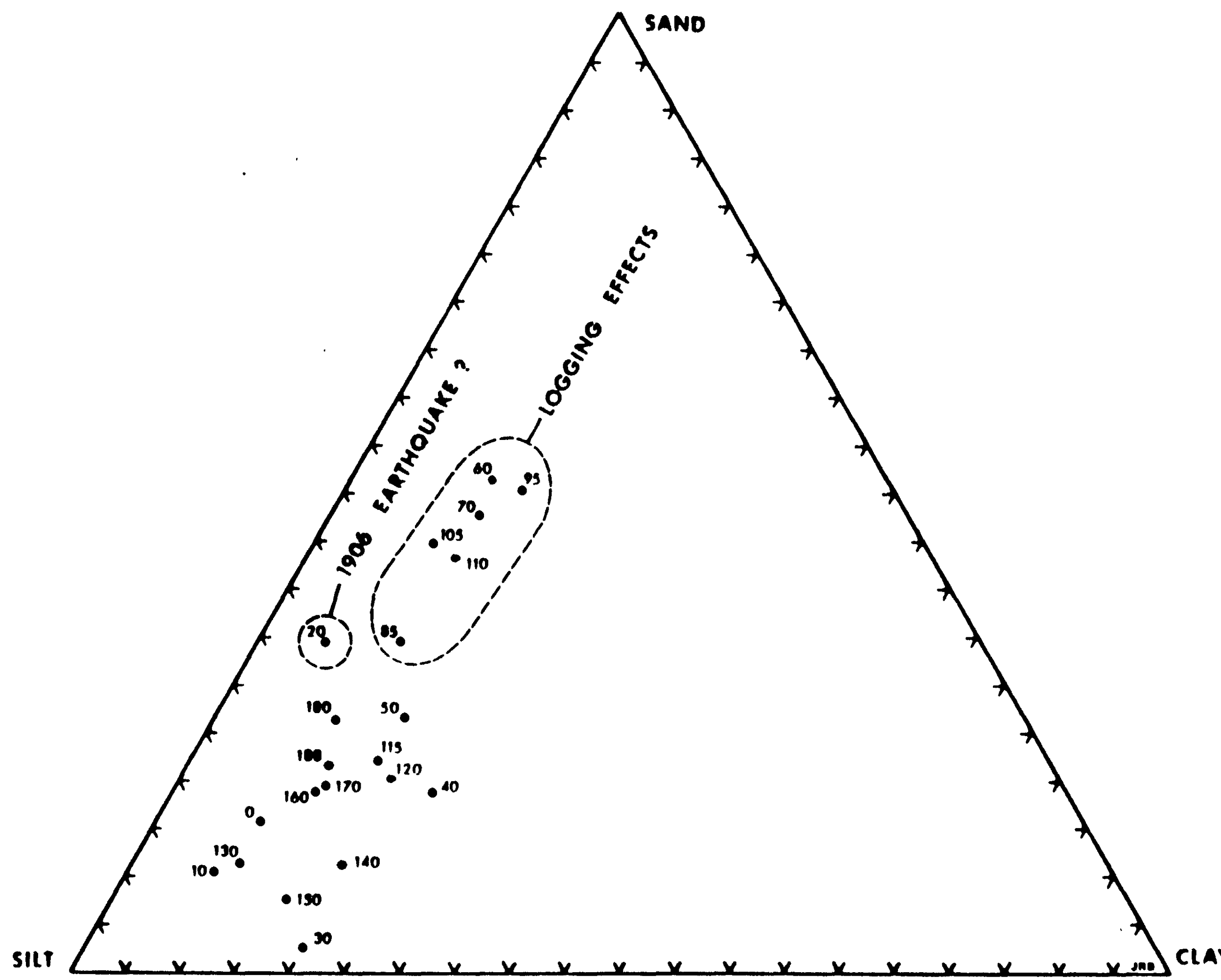


Figure 25. Triangular diagram showing percentages of sand, silt and clay for samples from core 6-76 taken in the Upper Basin of Bolinas Lagoon. Numbers indicate depth below surface in cm. Numerical values are listed in Table 4.

increasingly fine grained up to the 20-cm level where there is an anomalously coarse-grained sediment possibly resulting from disturbances related to the 1906 earthquake. Sediments above the 20-cm level again become finer grained.

Semi-quantitative mineralogical changes in core 6-76

X-ray powder diffraction of samples from core 6-76 was done to determine semiquantitative mineralogic changes that might correspond to changing patterns of sedimentation in the lagoon. Patterns for samples from 0, 10, 95, 105, and 130 cm were analyzed for semiquantitative changes in the following: aegerine-augite, K-feldspar, plagioclase, pyrite, quartz, chlorite, illite-muscovite, and montmorillonite. It was thought that the effects of logging might affect mineralogic distribution, but the observed changes were generally unsystematic and failed to coincide with changes in grain size. The highest amounts of chlorite were observed above the 10-cm level and below the 120-cm level. Thus, chlorite shows a negative correlation with largest mean grain size.

Because small copper mines were worked in the hills east of the lagoon as early as 1863 (Aubury, 1905) and operated intermittently until the 1930's, the X-ray patterns were scrutinized for an influx of diagnostic copper and lead sulfide minerals that might be used to provide a maximum-age datum. The only sulfide determined, however, was pyrite. The abundant organic material in the sediments is likely to cause reducing environments favoring formation of sedimentary pyrite, probably hydrotroilite, and therefore it is likely that the pyrite found in core 6-76 is authigenic, although detrital pyrite cannot be ruled out. Detrital pyrite may come from erosion of metallized zones in the Franciscan rocks and the erosion of Franciscan spilites.

Rates of sediment accumulation

Dated sedimentary and pollen horizons can be used to calculate rates of sediment accumulation in the north end of Bolinas Lagoon for several time periods within the last 120 years. The three dated core horizons include (1) the 115- to 110-cm core segment, in which major changes in grain size and organic content are correlated with the beginning of large-scale logging in 1849, (2) the 70-cm core level, which contains the first *Eucalyptus* pollen, thought to have been deposited in the period 1875-80, and (3) the 20-cm core level, which shows a sharp increase in mean grain size that may be correlative with the 1906 earthquake. Rates of sediment accumulation were calculated using high and low values for core levels and dates, and reflect (1) intermittent core sampling and (2) uncertainties in the time of first appearance of *Eucalyptus* pollen.

The highest average rates of sediment accumulation, up to 1.9 cm/yr, are calculated for core segments 1 and 2 (table 6). These core segments include sediments from the period affected by large-scale

Table 6.--*Rates of sediment accumulation in core 6-76*

Core segment co.	Core levels	Dates	Accumulation dates
1	115-110 to 70 cm	1849 to 1875-1880	1.3-1.7 cm/yr
2	70 to 30-20 cm	1875-1880 to 1906	1.3-1.9 cm/yr
3	30-20 to 0 cm	1906 to 1976	0.3-0.4 cm/yr
4	115-110 to 30-20 cm	1849 to 1906	1.4-1.7 cm/yr
5	70 to 0 cm	1875-1880 to 1976	0.7 cm/yr
6	115-110 to 0 cm	1849 to 1976	0.9 cm/yr

logging (1849 to 1875-1880) and the coarse-grained sediments related to the 1906 earthquake. These high rates of sediment accumulation were probably caused by increased erosion resulting from lumbering activity. Concentrations of pollen decrease where rates of sediment accumulation are high.

The lowest average sediment accumulation rate, 0.3 cm/yr, is calculated for core segment 3 (table 6) which represents the 1906(?) to 1976 period, a time of fine-grained sedimentation with no indications of major sedimentary changes. The overall average sediment accumulation rate is 0.9 cm/yr. The intermediate values are averages of calculated accumulation rates. For example, the rate of 0.7 cm/yr calculated for core segment 5 includes averaging of low-sediment accumulation rates for the post-1906 period with higher rates for the 70- to 50-cm core segment that was deposited in the period affected by logging.

To summarize, logging around Bolinas Lagoon apparently resulted in high average rates of sediment accumulation of 1.3 to 1.9 cm/yr at the site of core 6-76; the post-1906 period is characterized by much lower sediment accumulation rates ranging from 0.3 to 0.4 cm/yr; and rates calculated for other periods in table 6 involve averaging of high and low accumulation rates.

Effects of floods on sedimentation

Episodic flooding or abnormally high rainfall may in part cause changes in rates of sediment accumulation in the lagoon. Gilbert (1908) noted that floods in March 1907 obscured the fault trace on Pine Gulch Creek delta. The influx of coarser sediments at the 20-cm level may thus result from a combination of flooding in 1907 and ground breakage resulting from the 1906 earthquake. Broken ground is easier to erode, and heavy rains and consequent floods may have moved abnormally high amounts of sediment into the lagoon. Increased stream velocities during heavy rains and floods may account for transport of coarser material into areas of generally fine-grained deposition, such as the Upper Basin. Janda (1976) indicates that the amount of watershed erosion along Redwood Creek, Calif., during severe rainstorms in 1953, 1955, 1964, 1972, and 1975 was substantially influenced by watershed disturbances resulting from intensive logging.

Other floods in the San Francisco Bay region were recorded for the years 1798-99, 1819, 1849-50, 1852-53, 1861-62, 1867, 1869, 1871, 1874, 1878, 1879, 1881, 1889-90, 1895, 1903, 1909, and 1911 (McGlashan and Briggs, 1939). Floods have occurred numerous times since 1911 as well; but the general homogeneity of core sediments above the 20-cm level of core 6-76 suggests that in the Upper Basin of Bolinas Lagoon, floods do not cause obvious changes in grain-size parameters. This implies that changing patterns of grain-size in the core are largely caused by factors other than flooding.

Long-term sediment accumulation

Radiocarbon dates on shells taken from borehole 3 & 6 permit calculation of long-term sediment accumulation rates that can be compared with short-term rates determined from analysis of sediments in core 6-76. Radiocarbon dates from borehole 4 were not used to calculate long-term rates of sediment accumulation because dated horizons in that borehole have apparently undergone tectonic subsidence. A summary of radiocarbon data and accumulation rates is given in table 7. Several bivalve species identical to those dated weather out of the Pliocene Merced Formation in the Bolinas Cliffs just west of the inlet. The dated shells were relatively unabraded and appeared to be unreworked, hence not Pliocene, although this possible source of contamination exists.

A date of 1,160±60 years B.P. was obtained at 7.9-8.2 m below the surface, and a date of 6,450±100 years B.P. was obtained at 15.25 m. The younger data was corrected to 1,110±50 years B.P. by tree-ring correlation (Seuss, 1970). The older date could not be corrected because it exceeds present limits of tree-ring corrections for radiocarbon dates.

Rates of sediment accumulation were calculated using corrected dates where possible and by using ages corresponding to one standard deviation limits in order to achieve a range of rates based upon the 68 percent confidence level. Sediment accumulation rates derived from borehole 3 & 6 radiocarbon dates are (1) 0.7-0.8 cm/yr for 7.9-8.2- to 0-m segment, (2) 0.2 cm/yr for the 15.25- to 0-m segment, and (3) an overall average rate of 0.3 cm/yr for the 15.25- to 0-m segment. The highest sediment accumulation rates occur in the upper borehole segment and may be explained in part by the following: (1) the top 1.7 m of the borehole sediments are dune sands that, because of their mobility, have a potential for extremely high accumulation rates, (2) the use of a corrected date, 50 years younger than the corresponding uncorrected date, which yields higher accumulation rates, and (3) the uncompacted nature of the near-surface sediments.

Average rates of sediment accumulation for the last 6,450±100 years of 0.3 cm/yr are equal to or slightly less than the post-1906 rates of 0.3-0.4 cm/yr measured at the site of core 6-76. This indicates that sediment accumulation rates for the past 70 years in the north end of the lagoon are slightly higher than the average long-term Holocene rates, and dramatizes the anomalous nature of the high accumualtion rates of 1.3-1.9 cm/yr (table 6) calculated for the period affected by logging that are four to six times greater than the long-term Holocene rates.

Table 7.—*Radiocarbon dates and rates of sediment accumulation*

U.S.G.S. Radiocardon I.D. Number	Material dated[1]	C^{14} Age	Tree-ring corrected age	Latitude/ longitude	UTM coordinates	Depth below surface	Rates of sediment accumulation
USGS-71	Bivalves: Macoma nasuta Tresus sp.	1160 ± 60	1110 ± 60	37°54'28.27"/ 122°40'39.49"	Northing: 4195434.7 Easting: 528338.7	7.9-8.2 m	:to surface 0.7-0.8 cm/yr
USGS-72	Bivalves: Macoma nasuta Tresus sp. Clinocardium nuttalli Protothaca staminea	6450 ± 100	--	37°54'28.27"/ 122°40'39.49"	Northing: 4195434.7 Easting: 528338.7	15.25	:to surface 0.3 cm/yr :to 7.9-8.2 m level 0.2 cm/yr

[1]Identified by W. O. Addicott, U. S. Geological Survey, Menlo Park, Calif.

Summary and conclusions

Sediment type and rates of sediment accumulation have changed significantly in the northern part of Bolinas Lagoon during the past 125 years because of man's activities and seismic shock. These changes were determined by analyses of pollen, sediment, and organic-content of core 6-76 taken in a tidal flat near the 1906 trace of the San Andreas fault 1 km north of Pine Gulch Creek.

The pollen of three plant species introduced into the Bolinas area in the mid-19th-century were used to establish time horizons used to calculate sediment accumulation rates. On the basis of first known Eucalyptus plantings near the lagoon in the early 1870's, pollen probably first occurred in the period 1875-80 (70-cm core level). Grain-size analysis in conjunction with rates of sediment accumulation permitted calculation of dates of introduction for R. acetosella (1857-59) and P. lanceolata (1868-73) into the vicinity of Bolinas Lagoon.

The presence of Macoma nasuta raised the possibility of pollen transport down the core, with consequent uncertainty in dates of introduction for the three alien plant species. Because first appearance of the three alien pollen types occurred in the 115- to 50-cm core segment that is characterized by scarce, very small bivalves, it is inferred that pollen disturbance was minimal.

Changes in grain-size parameters and pollen also indicate:

1. Increased erosion of the watershed caused by 19th-century logging. Relative to core segments above and below, the 115- to 50-cm segment is characterized by larger mean grain size, poorer sorting, higher gravel/sand and sand/mud ratios, minimum amounts of bivalves, abundant plant debris, including redwood(?) chips, and low pollen concentrations of pine, oak, alder, Cheno-ams and TCT (pl. 14).

2. At the 20-cm level an anomalous sediment characterized by large mean grain size, higher positive skewness, and a high sand/mud ratio indicates an influx of coarser grained particles into an area of fine-grained sedimentation and may be correlative with the 1906 earthquake.

3. The highest average rates of sediment accumulation determined in core 6-76 are 1.3-1.9 cm/yr for the 1849-1906 period. This corresponds to the 115- to 20-cm core segment, and includes both the 115-to 50-cm segment affected by logging and the 20-cm level that may be affected by the 1906 earthquake. Decreased pollen concentrations indicate that high sediment accumulation rates occured in the 115- to 40-cm core segment (pl. 14), probably resulting from increased erosion in the watershed due to logging from 1849 to the late 1850's and, to a lesser extent, from cordwood logging between 1849 and 1880.

4. Rates of sediment accumulation for the post-1906 period (20-0 cm) range from 0.3 to 0.4 cm/yr, and are lower than those calculated for the 1849-1906 period. Decreasing accumulation rates probably reflect stabilization of the watershed around Bolinas Lagoon, and may result from reforestation of logged areas, and the reduction of cattle grazing in the hills around the lagoon with the possibility of consequent succession of *Gramineae* (grasses) and *Plantago lanceolata* by *Quercus* (oak) in the top 30 cm of the core.

5. Calculations utilizing radiocarbon dates on the shells from borehole 3 & 6 indicate an average sediment accumulation rate of 0.3 cm/yr for the past 6,450±100 years. The long-term rates are equal to or slightly less than post-1906 rates of 0.3-0.4 cm/yr calculated for core 6-76. Accumulation rates obtained for the 1849-1906 period (115-20 cm) of 1.3 to 1.9 cm/yr are four to six times higher than average Holocene rates of 0.3 cm/yr and demonstrate the anomalously high sediment accumulation rates during the period affected by logging.

PHOTOGRAPHIC RECORD OF CHANGE IN BOLINAS LAGOON, 1906/1907 - 1976/1977

After the 1906 earthquake, Gilbert (1908) photographed and described its effects in the area from Bolinas Lagoon to Tomales Bay. The sites from which Gilbert photographed several previously unpublished views of the lagoon were reoccupied and the same views rephotographed (fig. 26). Comparisons of photographic pairs from 1906/1907 and 1976/1977 reveal significant changes in the lagoon during the last 70 years.

Water-depth corrections

Photographs taken from Bolinas Ridge March 14, 1977, (fig. 27b, 28b) and March 8, 1907, (figs. 27a, 28a) demonstrate sediment accumulation in the lagoon because they were taken at times of similar water depth. Gilbert (1906-07) recorded the date and stage of the tide for figures 27a and 28a, and this permitted accurate comparisons, because with certain corrections the depth of water in the lagoon at the time of the 1907 photographs could be determined.

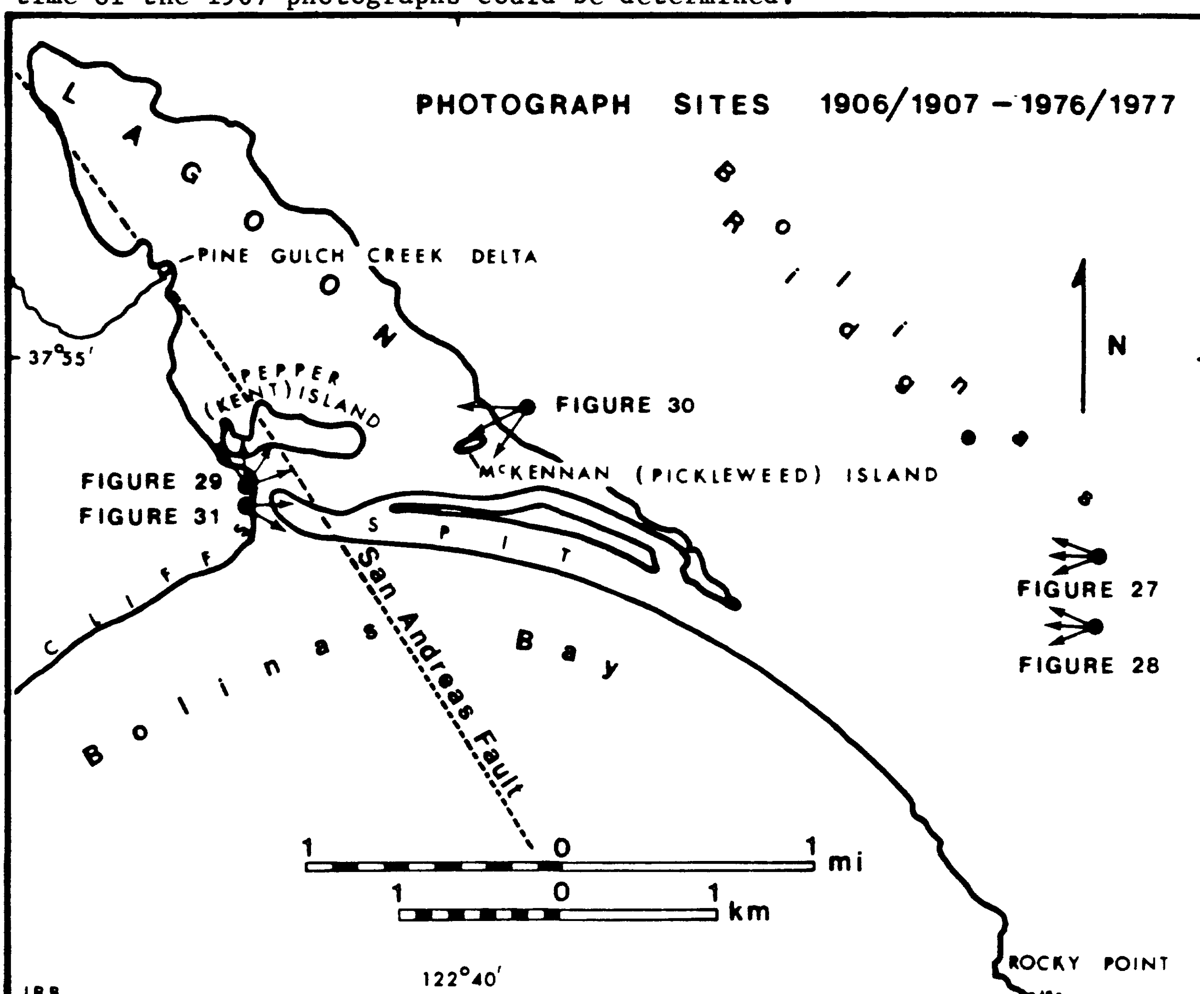


Figure 26. Map of Bolinas Lagoon showing locations of photographs taken in 1906/1907 and 1976/1977 for comparison. Arrows indicate direction of photography.

To determine tide levels in the lagoon for Gilbert's photographs, 1907 tide tables (U.S. Coast and Geodetic Survey, 1906) were consulted. Corrections were then made for rising sea level since 1907 to compensate for today's greater tidal prism.

Figure 27a was photographed "about two hours before low water in the lagoon," and figure 28a "about one hour before low water in the lagoon," (Gilbert, 1906-07). Tide tables (U.S. Coast and Geodetic Survey, 1906) indicate that the level of the single low tide March 8, 1907, was 0.0 feet with respect to mean lower low water (MLLW) at San Francisco. Consequently, but for sea-level changes in the interim, a 0.0 tide at San Francisco is suitable today for comparative photography. Rising sea level since 1907, however, necessitates a low tide below 0.0 feet at San Francisco in order to make water levels equivalent for the 1977 and 1907 low tides.

Tide guage records at San Francisco indicate a 0.3-foot net rise in mean sea-level between 1907 and 1968 (Hicks, 1968), and the total rise by 1977 may be slightly greater than this. A low tide of -0.3 feet to perhaps -0.35 feet at San Francisco is thus the equivalent of a 0.0 low tide in 1907. Assuming net sea-level rise at Bolinas Lagoon is the same as at San Francisco, the -0.3 to -0.35-foot low tides will duplicate lagoonal bathymetry that existed in 1907 at similar tidal stages. Rephotographing of figures 27a and 28a was done relative to -0.3-foot-low tides so that observed changes in exposed tidal flats at similar tide levels would probably represent minimum changes. In determining times of 1 and 2 hours before low tide, a +31-minute correction was made for the time difference between low tide at San Francisco and Bolinas Lagoon pusuant to 1977 tide tables (National Ocean Survey, 1976).

Although care was taken to rephotograph figures 27a and 28a at similar water levels, several other factors may affect the accuracy of matched water levels of 1907 and 1977. Barometric pressures and wind affect tide levels, with low-pressure systems and onshore winds causing raised water levels, and high-pressure systems and offshore winds the reverse.

At 1450 hrs March 14, 1977, about 30 minutes after predicted low tide in the lagoon, the barometric pressure was a steady 1012.5 millibars. This compares with an interpolated barometric pressure of 1013.9 millibars at 1300 hours about 10 minutes after predicted low tide March 8, 1907. These reading are from the San Francisco weather station, and it is assumed similar conditions existed approximately 20 km north at Bolinas Lagoon. The difference in barometric pressure for the two dates is negligible and therefore not significant with respect to tide levels.

On March 14, 1977, at 1400 hrs, near the time of low tide, there were variable light winds from the east at 4 to 5 mph, shifting by 1600 hrs to the southwest at 10 to 11 mph. On March 8, 1907, at 1100 to 1200 hrs, winds were variable light, from the northeast at 3 to 4 mph, shifting by 1700 to the southwest at 12 mph. Wind conditions on the two days are very similar, and their effect on tidal levels would also be similar. Because the winds were light and generally offshore near times of low tide, the tide levels in the lagoon were probably little affected by them on either date. The tide and weather data are summarized in table 8 for days on which the lagoon was photographed from Bolinas Ridge.

Tidal flats

Comparison of figures 27a and 28a, photographed in 1907, with figures 27b and 28b, which were rephotographed in 1976, shows an increase in the area of tidal flats exposed at comparable tidal stages, and gives a qualitative indication of sediment accumulation in the lagoon during the past 70 years. The photographic comparisons indicate that the areas of greatest visible sediment accumulation since 1907 are (1) north (lagoonward) of the spit, (2) east and northeast of Kent Island (figs. 28a and 28b, point A), and (3) the distal parts of Pine Gulch Creek delta (figs. 28a and 28b, point F; figs. 29a and 29b, point B).

Spit

Washover fans are seen as the cuspate forms on the north side of the spit in figures 27a and 28a (point C) and were formed by waves overtopping the spit. This overtopping became more frequent after the 1906 earthquake, probably because of subsidence of the spit east of the 1906 trace of the San Andreas fault (Gilbert, 1908). In the early 1960′s, most of the washover fans were dredged, and the spoils used to build an extension of the spit for the Seadrift development (figs. 27b and 28b, point C). The washover fans are also seen in figure 31a (point A), and comparison with figure 31b (point A) shows the man-made extension of the spit and the dredged recreational lagoon now occupying the position of the 1907 washover fans.

The distal end of the spit, the part closest to the viewer in figures 31a and 31b, is covered with small dunes 1 to 2 m high in both the 1906 and 1976 views. The approximate 1906 trace of the San Andreas fault (fig. 31a, line F-F′) lies at the boundary between the dune field (fig. 31a, point B), and the low areas of the spit in the distance. The 1976 photograph (fig. 31b, line F-F′) shows the dunes now extending along a ridge on the ocean side of the spit, which was topographically low in 1907 (fig. 31a). The primary reason for the increase of dune sand along the axis of the spit is stabilization by man. The houses and cultivated vegetation that now extend nearly the entire length of the

Table 8.--*Tide and weather statistics for Bolinas Lagoon photography 1907/1977*

[Data from U.S. Weather Bureau, San Francisco, Calif.; National Climatic Center, Asheville, N. C.; U.S. Coast Survey and National Ocean Survey (1976).]

Day	Time of low tide at San Francisco (Golden Gate)	Predicted height (ft)	Wind (mph)(time)	Barometric pressure (millibars)(time)
March 8, 1907	1252	0.0	Calm, S 1 (0500) Variable light NE 3-4 (1100-1200) Variable light NW 3-4 (1200-1300) Variable light SW 12 (1700)	falling 1014.9 (0500) 1013.9 (1300)[1]
March 14, 1977	1349	-0.3	Variable light E 4-5 (1400) Variable light SW 10-11 (1600)	steady 1012.5 (1450)

[1]Interpolated value

spit act as traps to inhibit aeolian transport of sand from the beaches over the spit.

The shoreline configuration of the inlet is very similar in figures 31a and 31b, but as discussed previously, it changes greatly depending upon year, season, and stage of the tide.

Pepper (Kent) Island

Comparison of figures 29a and 29b shows significant sediment accumulation on Kent Island since 1907. The island area closest to the viewer has built up and narrowed the secondary tidal channel in the foreground. The light-colored, sandy ground on which the cluster of Monterey cypress (Cupressus macrocarpa) grows (fig. 29b, point A) is now above MHHW. Extensive areas northeast of Pepper (Kent) Island (fig. 29a, point E) filled in and developed Salicornia marsh after 1907. The large area of tidal flats south of Pine Gulch Creek delta (fig. 29a, point G) also became marsh by 1976, and a wide channel which flowed there shifted farther south (figs. 29a and 29b, point F). Pine Gulch Creek delta and nearby tidal flats apparently prograded more than 100 m since 1907 (figs. 29a and 29b, point B; 28a and 28b, point F).

The approximate 1906 trace of the San Andreas fault is marked by the vestiges of the Kent Island channel, which progressively narrowed after 1929 (fig. 15) and today is represented by a shoreline indentation on the south side of Kent Island (fig. 29b, point E) and by an alinment of water-filled depressions (fig. 29b, line E-E′). During the 1906 earthquake, Salicornia marshes east of this line (away from the viewer) were downdropped approximately 30 cm, and the resulting increase in duration of tidal submergence caused destruction of the marshes there (Gilbert, 1908).

McKennan (Pickleweed) Island

Comparison of figures 30a and 30b (point A) shows that since 1907 McKennan (Pickleweed) Island has been eroded to less than 10 percent of its former size. Figures 27a and 27b (point B) taken from Bolinas Ridge also show the reduction in size of the island. Most of the erosion was apparently caused by the southeast migration of the main channel, which is indicated in figure 30b (point D) by an S-shaped line of current ripples to the right of the island. Examination of the island February 7, 1976, showed the Salicornia marsh being undercut on the north side and resultant slumping. Along this erosional scarplet, numerous roots from large shrubs of the genus Atriplex(?) (salt-bush) were found, and indicate that the island was formerly at a higher elevation because shrubby species of Atriplex are not typically found in central California salt marshes. Measurement of offset along the boundary between healthy and deteriorated marshes after the 1906 earthquake indicated at least 25 cm of subsidence of McKennan (Pickleweed) Island (Gilbert, 1908). This subsidence may have ultimately caused the death of the shrub or bush seen growing on the northwest side of the island in the 1907 photograph (fig. 30a).

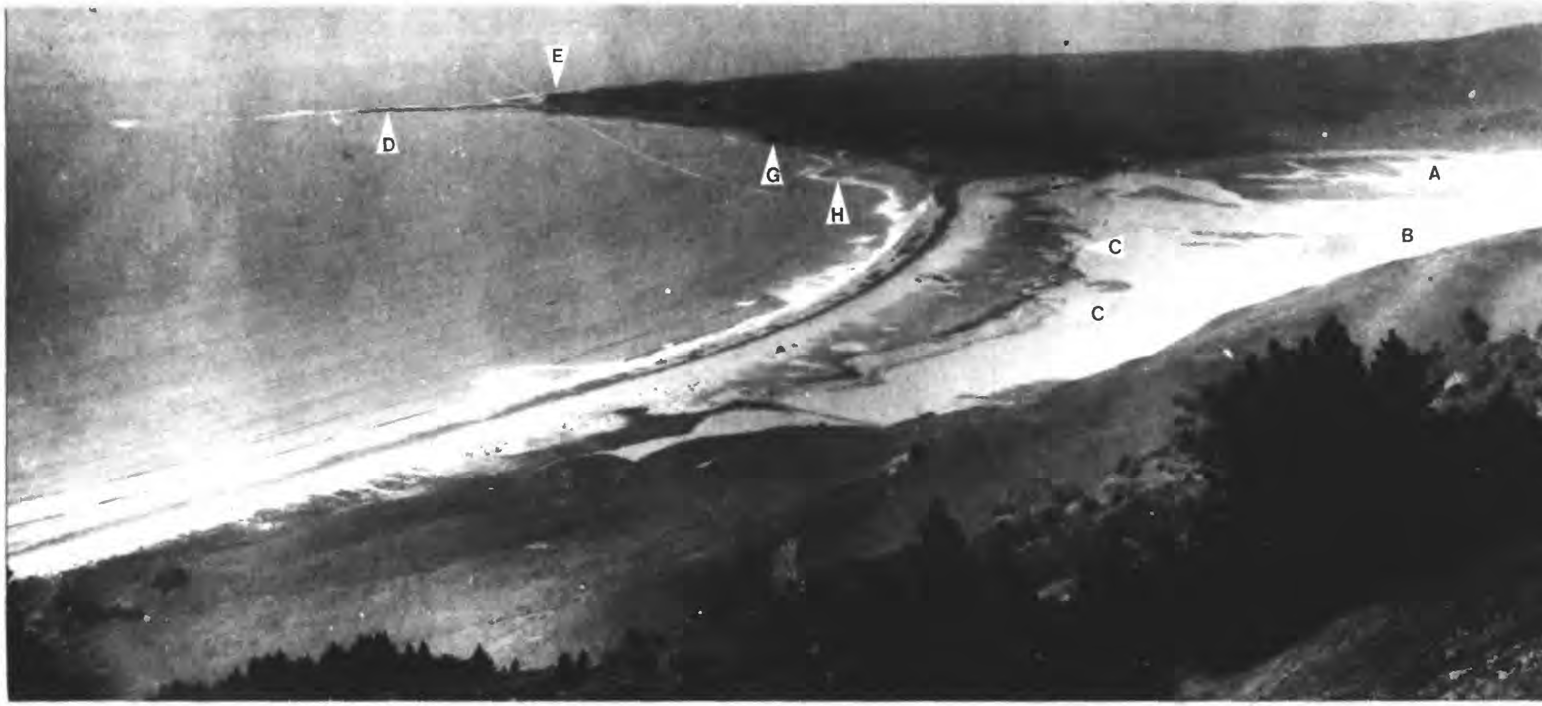


Figure 27a. Bolinas Lagoon, looking east from Bolinas Ridge. Photograph by G. K. Gilbert, 8 March 1907, 2 hours before low water in the lagoon. (A) Pepper (Kent) Island (B) McKennan (Pickleweed) Island (C) washover fans (D) Duxbury Reef (E) Duxbury Point (F) Pine Gulch Creek delta (G) the "clam patch," a wave-cut platform (H) ebb-tide delta.

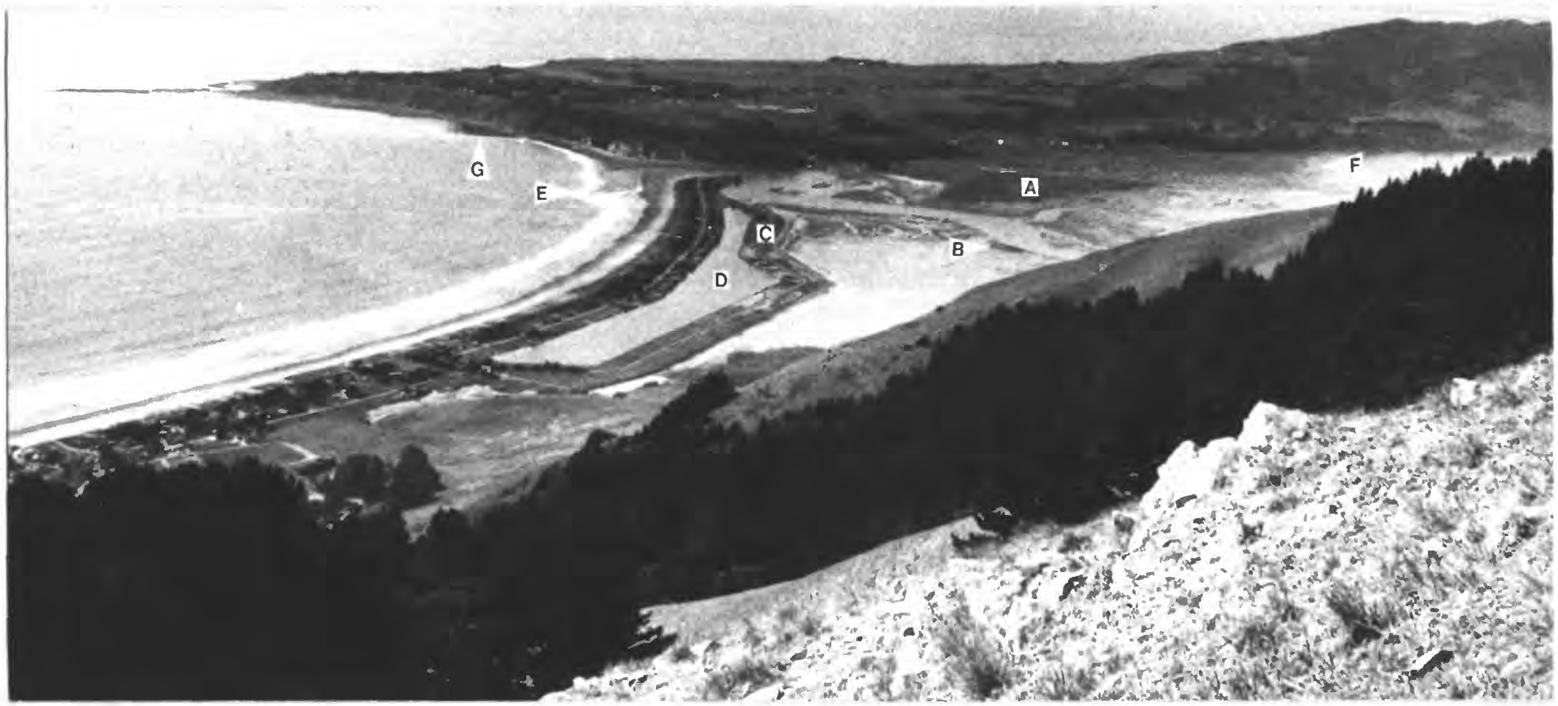


Figure 27b. Bolinas Lagoon, view from location of figure 27a, 14 March 1977, 2 hours before low water in the lagoon. (A) Kent (Pepper) Island (B) Pickleweed (McKennan) Island (C) filled extension of spit (D) Seadrift lagoon (E) ebb-tide delta (F) Pine Gulch Creek delta (G) the clam patch, a wave-cut platform.

Figure 28a. Bolinas Lagoon, looking west from Bolinas Ridge. Photograph by G. K. Gilbert, 8 March 1907, 1 hour before low water in the lagoon. (A) Pepper (Kent) Island (B) McKennan (Pickleweed) Island (C) washover fans (D) Duxbury Reef (E) Duxbury Point (F) Pine Gulch Creek delta (G) clam patch, a wave-cut platform (H) ebb-tide delta.

Figure 28b. Bolinas Lagoon, view from location of figure 28a, 14 March 1977, 1 hour before low water in the lagoon. (A) Kent (Pepper) Island (B) Pickleweed (McKennan) Island (C) filled extension of spit (D) Seadrift lagoon (E) ebb-tide delta (F) Pine Gulch Creek delta (G) the clam patch, a wave-cut platform.

Figure 29a. Panoramic view of Pepper (Kent) Island looking north from bluff above Bolinas harbor. Photographs by G. K. Gilbert, April 1907. (A) Pepper (Kent) Island (B) Pine Gulch Creek delta (C) main tidal channel (D-D') Bolinas Ridge (E) area of post-1907 fill and marsh growth (F) position of secondary tidal channel in 1976 (G) area of post-1907 fill and marsh growth.

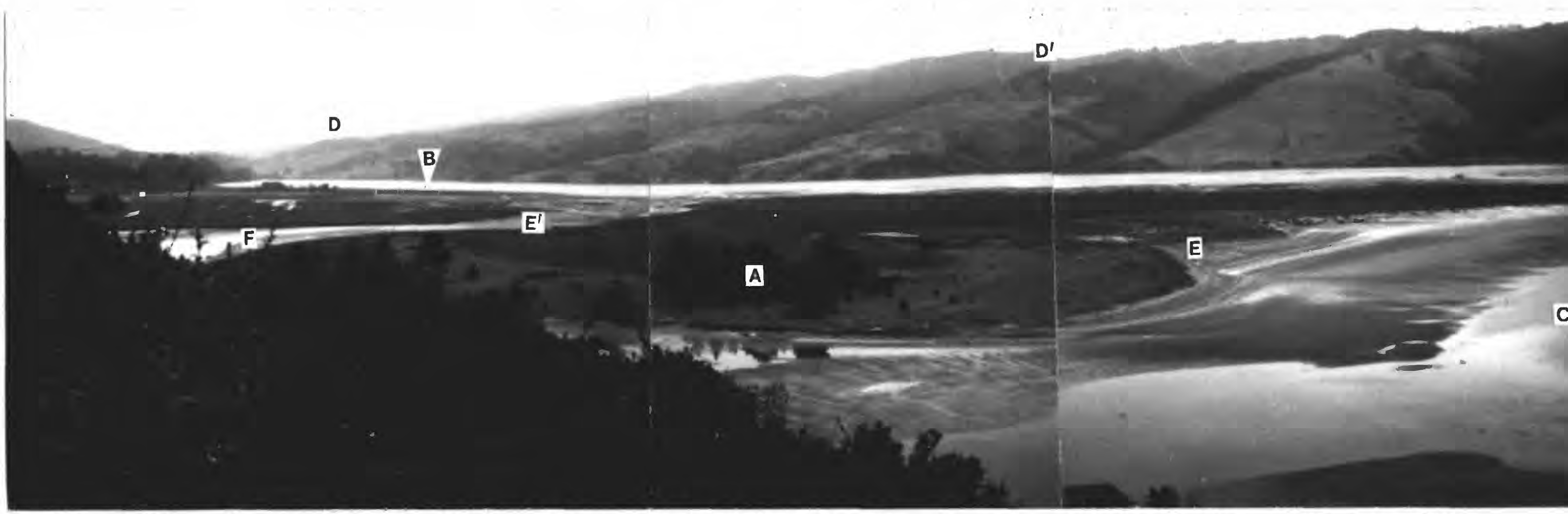


Figure 29b. Panoramic view of Kent (Pepper) Island, view from location of figure 29a, 1815 hrs. PDT 26 September 1976. (A) Monterey cypress grove on Kent Island (B) Pine Gulch Creek delta (C) main tidal channel (D-D') Bolinas Ridge (E-E') approximate 1906 trace of San Andreas fault marked by shoreline indentation and water-filled depressions, the vestiges of Kent Island channel (F) secondary tidal channel.

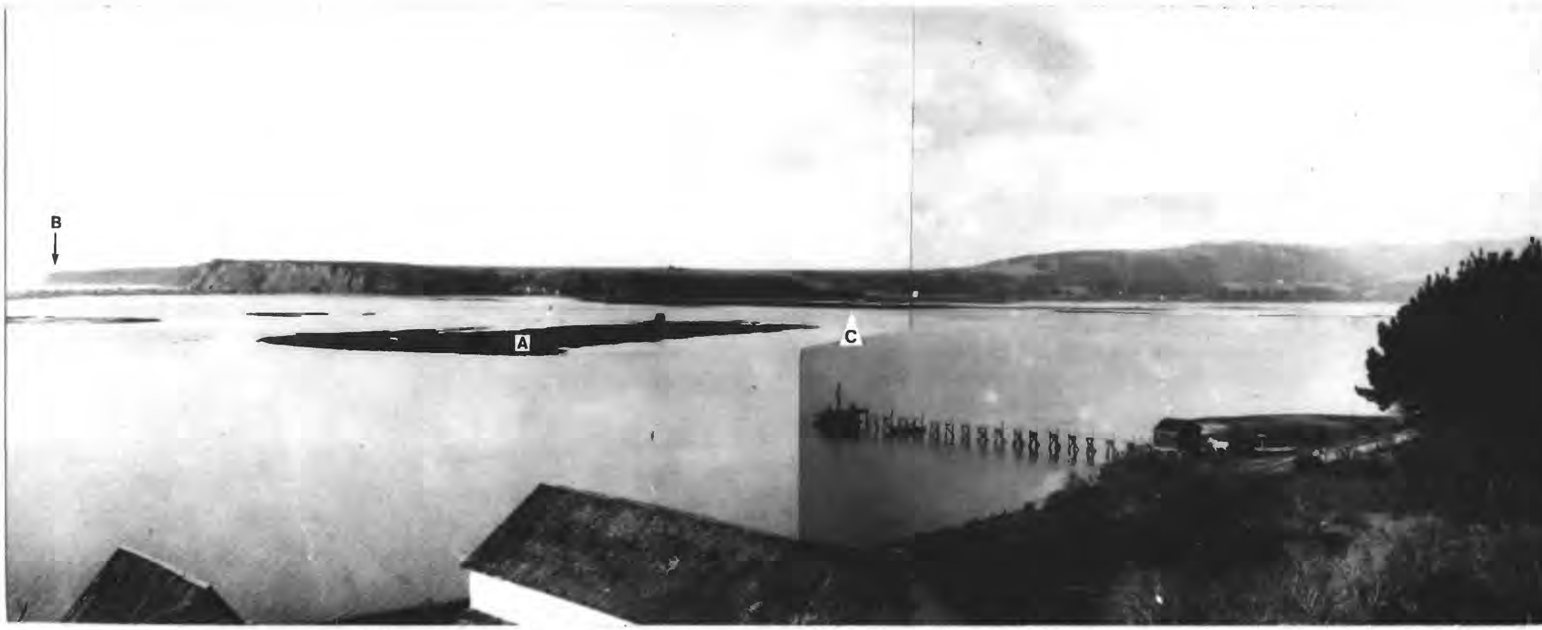


Figure 30a. McKennan (Pickleweed) Island, looking west from south side of McKinnan (sic) Gulch. Photographs by G. K. Gilbert, ca. 1907. (A) McKennan (Pickleweed) Island (B) Duxbury Point (C) Pepper (Kent) Island.

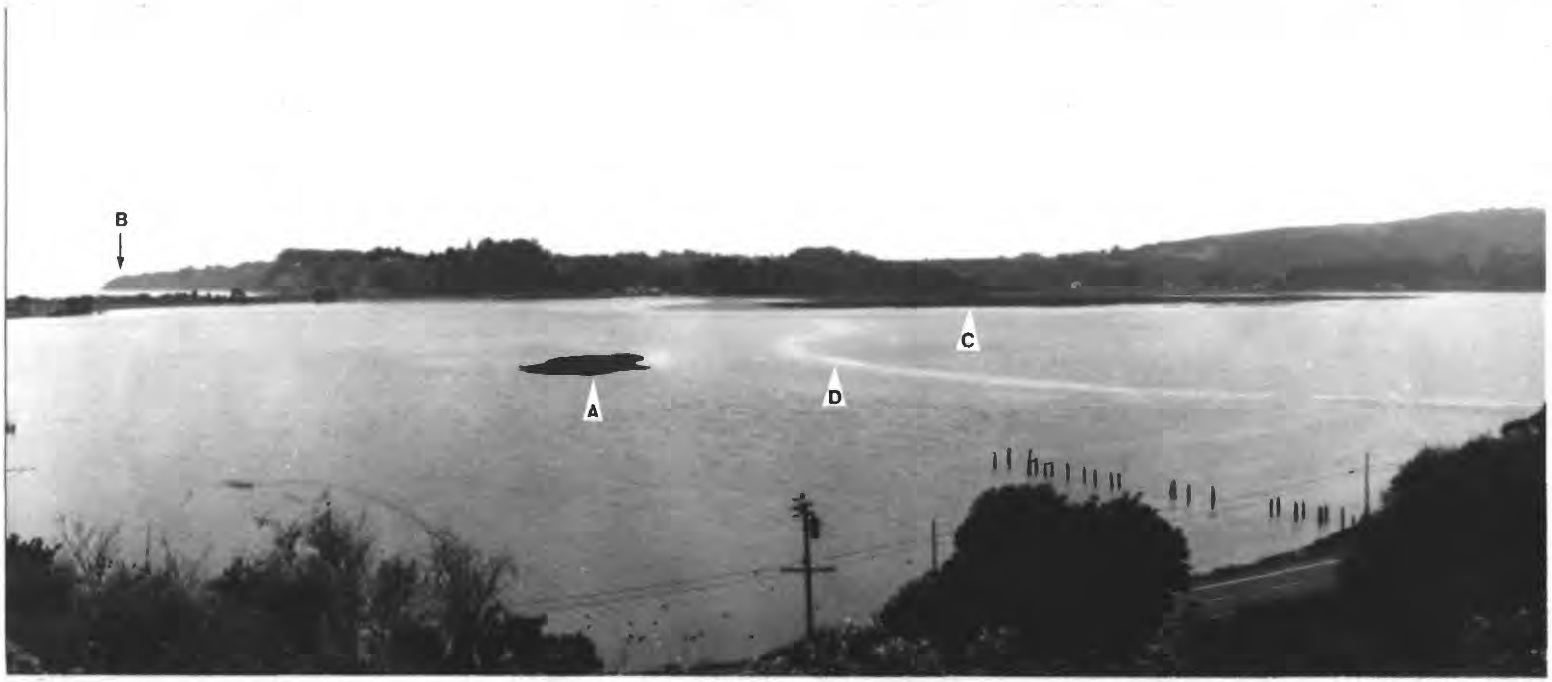


Figure 30b. Pickleweed (McKennan) Island, view from location of figure 30a, 1630 hrs. PDT, 26 September 1976. (A) Pickleweed (McKennan) Island (B) Duxbury Point (C) Kent (Pepper) Island (D) ripple marks showing approximate location of main tidal channel.

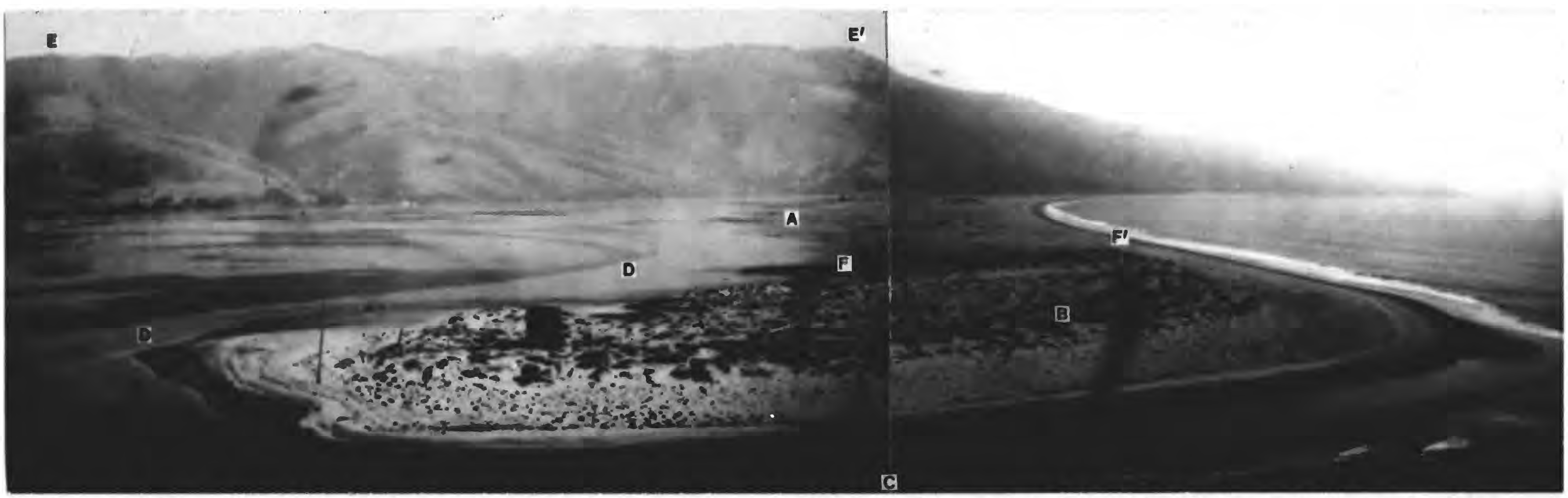
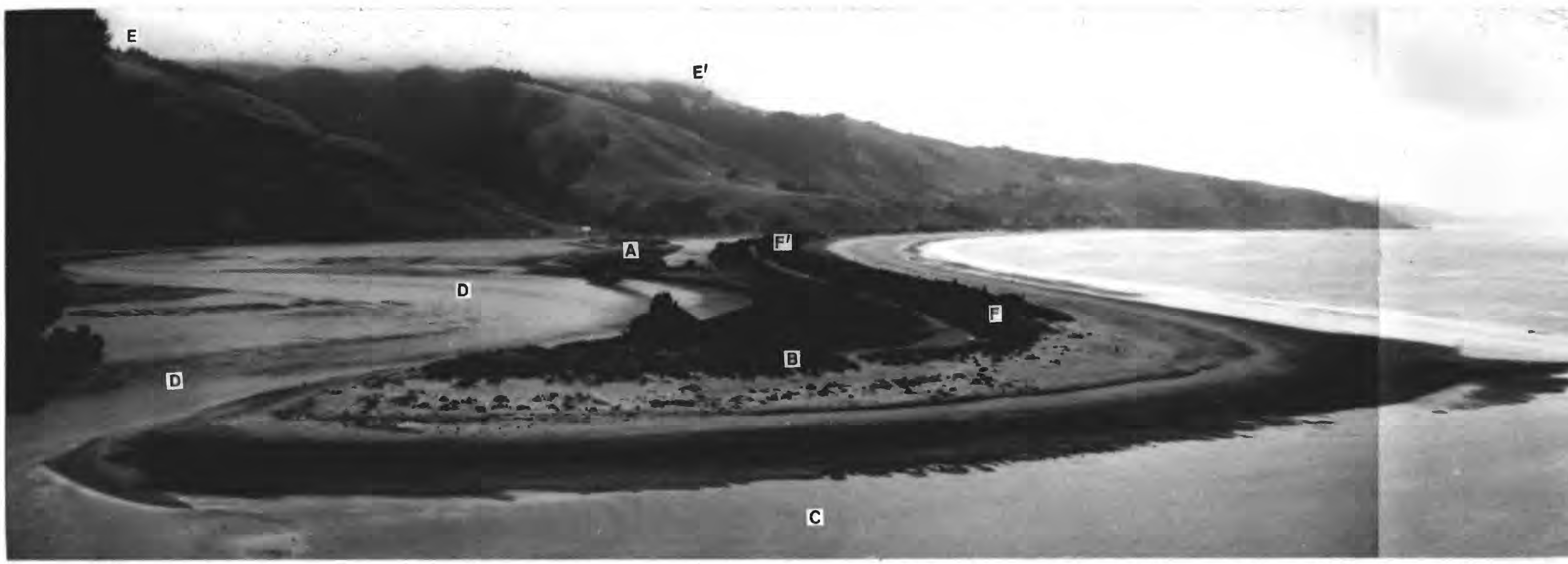


Figure 31a. Stinson Beach spit and Bolinas Lagoon (left), looking east from bluff above Bolinas harbor. Photographs by G. K. Gilbert 27 September 1906. (A) washover fans (B) dune field (C) tidal inlet (D) main tidal channel (E-E') Bolinas Ridge (F-F') approximate 1906 trace of San Andreas fault.



- Figure 31b. Stinson Beach spit and Bolinas Lagoon (left), view from location of figure 31a, 1830 hrs. PDT, 26 September 1976. (A) dredged extension of spit, position of 1907 washover fans (B) dune field (C) tidal inlet (D) main tidal channel (E-E') Bolinas Ridge (F-F') Seadrift development along dune ridge.

Figure 32. Coastal plain and Exmoor Hills at Porlock, North Devonshire, England. Former embayment or lagoon completely filled with sediment indicating possible future of Bolinas Lagoon. (Photograph courtesy of C. R. Twidale, University of Adelaide.)

Figures 30a and 30b (point B) also show apparent recession and a decrease in slope of the cliffs at Duxbury Point.

Summary

To summarize, comparisons of the 1906/1907 - 1976/1977 photographs indicate (1) an increase in exposed tidal flat areas since 1907 at similar stages of the tide, (2) enlargement of Pepper (Kent) Island, especially the northeast part, (3) sediment accumulation and marsh overgrowth of the nearshore areas south of Pine Gulch Creek delta, (4) progradation of Pine Gulch Creek delta, (5) man's destruction of the washover fans north of the spit, (6) dune growth along the axis of the spit, (7) lateral erosion of McKennan (Pickleweed) Island, and (8) cliff recession at Duxbury Point.

Together, these changes which occurred over a 70-year time span indicate the rapidity of change in this coastal lagoon, and suggest that the transition from shallow embayment to coastal plain is geologically very rapid.

Continued sediment accumulation in Bolinas Lagoon will ultimately fill the lagoon and convert it to a small coastal plain, assuming (1) that rates of sediment accumulation exceed tectonic or isostatic deepening of the basin, and (2) noninterference by man. A small, filled coastal embayment on the coast of North Devonshire, England (fig. 32), bears a striking resemblance to the Bolinas area and shows the ineluctable fate of Bolinas Lagoon.

SUMMARY AND CONCLUSIONS

Comparison of the composited U.S. Coast and Geodetic Survey topographic surveys of Bolinas Lagoon for 1854 and 1929 were used to plot the location of the 1906 trace of the San Andreas fault by (a) the linear boundary between 1854 and 1929 Kent Island salt marshes, (b) the position of Kent Island channel that apparently developed susequent to 1906 along the fault trace, and (3) azimuths of the fault trace on Kent Island measured by Gilbert (1908).

Significant changes in lagoonal morphology from 1854 to 1929 include:

Decrease in salt marshes on Kent Island east of the 1906 fault trace resulting from 30 cm of tectonic subsidence.

Decrease in back barrier salt marshes east of the 1906 fault trace resulting from tectonic subsidence and more frequent washover.

Widening of the spit, probably primarily due to increased washover.

Cliff recession between the lagoon inlet and Duxbury Point.

Recession of the MHW line on the ocean side of the spit, probably related to cliff recession west of the lagoon inlet.

Southeast migration of the main tidal channel causing erosion of Pickleweed Island.

Minor decreases in marsh areas at the head of the lagoon and along the east side, caused by man's activities and to a lesser extent, the 1906 earthquake.

Seismic reflection profiling revealed:

A graben fault near the east side of Bolinas Lagoon that may connect with an offshore graben fault on the Golden Gate Platform identified by Cooper (1973).

The position of the San Andreas fault in the main tidal channel along the southward extension of the boundary between the 1854 and 1929 marsh areas.

As much as 12.5 m vertical subsidence of the acoustic basement east of the San Andreas fault trace.

Approximately 5 m subsidence at a depth of 28 to 33 m west of the graben fault.

Acoustic basement may be the interface between unconsolidated marine and estuarine deposits and the underlying Pleistocene(?)-Holocene lacustrine muds.

A northwest-trending subsurface syncline along the east side of Kent Island.

Borehole logs of deposits beneath Stinson Beach spit indicate the area is underlain by complex discontinuous transgressive-regressive sequences of marine, estuarine, and barrier sediments that are underlain by lake or pond deposits. The lack of horizontal persistence of individual sedimentary units results from lateral and vertical shifting of depositional environments.

Radiocarbon-dated shells indicate the transgressive boundary at approximately 7,770±65 years B.P.

Megafauna recovered from boreholes indicate that post-transgression sediments were deposited in a very shallow water, protected, open coast estuary or bay. Vertical distributions of fauna suggest that the Bolinas Lagoon area was never a deep-water embayment, but continuously shallow with accumulation of sediment generally keeping pace with rising sea level.

Comparison of radiocarbon dates on shells and plant debris from boreholes with a relative sea-level curve constructed by Atwater and others (1977) for southern San Francisco Bay indicates:

No discernible tectonic subsidence west of the 1906 trace of the San Andreas fault.

5.8 to more than 17.9 m tectonic subsidence in borehole 4, near the east end of Stinson Beach spit. Because borehole 4 lies east of the graben fault identified by seismic profiling, it is inferred that another unverified fault with vertical displacement lies east of borehole 4 (fig. 22).

Profiles of fossil pollen recovered from lake or pond deposits beneath the transgressive boundary in borehole 4 indicate:

A Late-Pleistocene(?) cool, moist to wet climate with minimal annual fluctuations in temperature and rainfall, with frequent fog and low clouds during summer months.

An up-core sequence from perennial fresh water conditions to drier conditions with possible seasonal drying of the lake or pond.

A marine transgression between the 39- and 35-m core levels overlain by deposits that accumulated in a salt marsh or other shallow near-shore environment.

Analysis of grain-size parameters and pollen from a short core taken in the Upper Basin of Bolinas Lagoon indicates:

That redwood logging resulted in sediment changes at the 115-cm core level characterized by (a) a change in mean grain size from approximately 6 Ø to 5 Ø, (b) poorer sorting, (c) higher gravel/sand and sand/mud ratios, (d) appearance of abundant coniferous wood fragments, (3) lower pollen concentrations, and (f) fewer molluscs.

Prior to the beginning of logging in 1849, the lagoon bottom at the core site was as much as 115 cm deeper (with no allowance for sediment compaction) making this area probably subtidal.

Possible correlation of an anomalously coarse-grained sediment at the 20 cm level with the 1906 earthquake.

Average rates of sediment accumulation in the period 1849 to 1906 of 1.3 to 1.9 cm/yr.

Average rates of sediment accumulation in the post-1906 period of 0.3 to 0.4 cm/yr.

Average accumulation rates calculated from radiocarbon dates on borehole samples are as follows:

0.3 cm/yr above the 15-m level in borehole 3 & 6.

0.5 cm/yr above the 35-m level in borehole 4, reflecting increased sediment accumulation resulting from tectonic subsidence.

The post-1906 rates of sediment accumulation in the Upper Basin are thus approximately the same as long-term rates calculated with radiocarbon dates from borehole samples. The rates of sediment accumulation for the period 1849-1906 in the Upper Basin are three to six times as high as the post-1906 rates.

Comparison of photographs of Bolinas Lagoon taken in 1906/1907 by (Gilbert, 1906-07) with photographs taken in 1976/1977 reveal significant morphological changes in the lagoon, including:

An increase in tidal flat areas exposed at similar tidal stages.

Enlargement of Kent Island.

Growth of Pine Gulch Creek delta and extension of salt marshes in the west-central part of the lagoon.

Man's destruction of washover fans north of Stinson Beach spit.

Dune growth along the axis of the spit, primarily because of stabilization by man.

Erosion of as much as 90 percent of Pickleweed Island caused primarily by southeast migration of the main tidal channel.

Cliff recession at Duxbury Point.

Appendix A. Grain-size statistics for borehole samples

The formulae used in this report for computing the graphical statistics were derived by Folk and Ward (1957) and are as follows:

$$\text{Median} = \phi\,50$$

$$\text{Sorting} = \sigma_I = \frac{\phi\,84 - \phi\,16}{4} + \frac{\phi\,95 - \phi\,5}{6.6}$$

$$\text{Skewness} = \frac{\phi\,16 + \phi\,84 - 2\,(\phi\,50)}{2\,(\phi\,84 - \phi\,16)} + \frac{\phi\,5 + \phi\,95 - 2\,(\phi\,50)}{2\,(\phi\,95 - \phi\,5)}$$

$$\text{Kurtosis} = \frac{\phi\,95 - \phi\,5}{2.44\;(\phi\,75 - \phi\,25)}$$

The verbal limits of graphical grain-size parameters given below are modified after Folk and Ward (1957).

Sorting Ø	
<0.35	very well sorted
0.36 - 0.50	well sorted
0.51 - 1.00	moderately sorted
1.01 - 2.00	poorly sorted
2.01 - 4.00	very poorly sorted
>4.00	extremely poorly sorted

Skewness

-1.00 to -0.30	very negative-skewed
-0.29 to -0.10	negative-skewed
-0.09 to +0.10	nearly symmetrical
0.00	symmetrical
+0.11 to +0.30	positive-skewed
+0.31 to +1.00	very positive-skewed

Positive skewness indicates tail of fine grains.

Negative skewness indicates tail of coarse grains.

Kurtosis

<0.67	very platykurtic
0.68 to 0.90	platykurtic
0.91 to 1.11	mesokurtic
1.00	normal distribution
1.12 to 1.50	leptokurtic
1.51 to 3.00	very leptokurtic
>3.00	extremely leptokurtic

Leptokurtic curves are more peaked than a normal distribution.

Appendix A. Grain-size Statistics for Borehole Samples

BOREHOLE 2

Sample No.	Depth Below Surface (meters)	Moments ϕ				Graphical Statistics[1] ϕ				Sediment Ratios						Sediment Size Percentages[2]				
		M_1	M_2	M_3	M_4	Median	Sorting	Skewness	Kurtosis	Gravel/Sand	Sand/Silt	Silt/Clay	Sand/Clay	Sand/Mud	Gravel/Mud	Gravel	Sand	Silt	Clay	Mud[3]
2-1	3.0	2.09	1.36	1.32	8.84	2.06	0.70	-0.17	2.26	0.02	44.52	1.97	87.77	29.54	0.63	2.01	94.78	2.13	1.08	3.21
2-2	4.6	1.70	1.38	1.49	10.10	1.81	0.80	-0.39	1.94	0.02	137.98	0.58	79.93	50.61	1.11	2.11	95.99	0.70	1.20	1.90
2-3	6.1	0.78	2.23	0.30	2.40	1.01	1.62	-0.32	1.10	0.17	37.69	1.69	63.69	23.68	4.07	14.16	82.36	2.19	1.29	3.48
2-4	7.6	2.65	1.42	1.73	8.41	2.45	0.70	0.17	2.15	0.004	17.28	3.14	54.21	13.11	0.05	0.36	92.58	5.36	1.71	7.06
2-5	8.2	1.74	1.77	0.67	3.93	1.98	1.32	-0.47	1.73	0.07	35.06	2.00	69.94	23.36	1.70	6.53	89.63	2.56	1.28	3.84
2-6	9.1	2.39	1.29	2.24	12.10	2.09	0.54	0.58	1.65	--	25.89	2.55	65.92	18.59	--	--	94.90	3.67	1.44	5.10
2-7	9.8	2.97	2.06	1.19	2.91	2.44	1.29	0.50	2.77	0.01	8.87	2.42	21.51	6.28	0.03	0.47	85.86	9.68	4.00	13.67
2-8	10.7	2.02	1.64	2.03	9.37	1.79	0.56	0.12	1.48	0.01	123.29	0.29	36.24	28.01	0.13	0.44	96.13	0.78	2.65	3.43
2-9	12.2	2.38	1.12	2.51	16.35	2.24	0.48	0.05	1.14	--	38.42	2.29	88.11	26.76	--	--	96.40	2.51	1.09	3.60
2-10	13.7	2.20	1.29	1.51	10.35	2.13	0.67	0.01	1.47	0.01	34.32	2.37	81.20	24.13	0.33	1.31	94.76	2.76	1.17	3.93
2-11	15.2	2.58	1.46	1.69	7.32	2.33	0.84	0.27	2.60	--	15.34	3.69	56.56	12.06	--	--	92.35	6.02	1.63	7.66
2-12	16.8	3.17	1.91	1.35	3.61	2.51	1.17	0.61	4.27	--	8.83	2.43	21.42	6.25	--	--	86.21	9.77	4.03	13.79
2-13	18.3	3.04	1.76	1.52	4.76	2.60	1.03	0.47	4.47	--	9.82	2.73	26.76	7.18	--	--	87.78	8.94	3.28	12.22
2-14	19.2	4.63	2.68	0.55	0.13	3.50	2.51	0.59	1.15	--	1.40	3.23	4.52	1.07	--	--	51.66	36.91	11.43	48.34
2-15	19.8	3.03	1.77	1.39	4.17	2.60	1.11	0.38	3.48	--	8.63	3.50	30.19	6.71	--	--	87.03	10.09	2.88	12.97
2-16	21.3	3.16	2.07	1.21	2.86	2.51	1.41	0.56	3.14	--	7.71	2.38	18.37	5.43	--	--	84.45	10.96	4.60	15.56
2-17	22.9	3.52	2.30	0.91	1.36	2.67	1.90	0.63	2.29	--	4.19	3.36	14.08	3.23	--	--	76.36	18.22	5.42	23.64
2-18	24.4	2.67	1.55	1.58	6.13	2.38	0.95	0.29	2.53	--	11.96	3.95	47.26	9.55	--	--	90.52	7.57	1.92	9.48
2-19	25.9	2.93	1.66	1.44	5.06	2.50	1.03	0.43	3.15	0.01	10.18	3.53	35.94	7.93	0.04	0.40	88.45	8.69	2.46	11.15
2-20	26.5	2.71	1.44	1.65	7.03	2.49	0.82	0.19	2.88	--	12.45	4.66	58.04	10.25	--	--	91.11	7.32	1.57	8.89
2-21	27.4	2.75	1.46	1.67	7.16	2.53	0.83	0.18	2.63	0.001	12.66	4.00	50.67	10.13	0.01	0.06	90.96	7.19	1.80	8.98
2-22	28.0	3.37	2.05	0.97	1.96	2.69	1.68	0.60	2.52	0.003	4.50	4.80	21.57	3.72	0.01	0.22	78.64	17.49	3.65	21.14
2-23	29.0	3.17	2.42	0.93	1.54	2.49	2.04	0.52	2.38	0.004	5.85	2.28	13.34	4.07	0.02	0.30	80.03	13.67	6.00	19.67
2-24	29.6	2.23	1.36	1.60	8.36	2.16	0.86	-0.02	1.51	0.001	24.85	3.29	81.85	19.08	0.03	0.14	94.89	3.82	1.16	4.98
2-24A	29.6	2.39	1.63	1.74	7.79	2.26	0.80	-0.15	1.70	0.004	36.80	0.96	35.21	18.00	0.07	0.36	94.40	2.57	2.68	5.25
2-25	30.5	3.74	2.28	0.89	1.56	2.93	1.75	0.69	1.63	0.011	3.65	3.02	11.02	2.74	0.03	0.81	72.67	19.93	6.59	26.52
2-27	32.0	3.88	2.40	0.83	1.01	2.90	1.97	0.71	1.07	0.001	3.62	2.76	10.01	2.66	0.002	0.05	72.64	20.06	7.26	27.31
2-28	33.5	4.44	2.97	0.64	0.02	2.93	2.66	0.83	1.01	--	5.37	0.91	4.87	2.55	--	--	71.86	13.37	14.77	28.14
2-29	33.6	4.09	2.61	0.83	0.71	2.93	2.27	0.79	2.06	--	4.68	1.51	7.08	2.82	--	--	73.80	15.77	10.43	26.20

[1] Calculated using formulae of Folk and Ward (1957)

[2] Grains 3.5 phi (0.0880mm) were sieved; smaller grains were analyzed with a hydrophotometer.

[3] Mud = silt + clay

BOREHOLE 3

Sample No.	Depth Below Surface (meters)	Moments φ				Graphical Statistics φ				Sediment Ratios						Sediment Size Percentages				
		M_1	M_2	M_3	M_4	Median	Sorting	Skewness	Kurtosis	Gravel/Sand	Sand/Silt	Silt/Clay	Sand/Clay	Sand/Mud	Gravel/Mud	Gravel	Sand	Silt	Clay	Mud
3-1	0.6	1.94	0.98	1.65	14.30	1.99	0.60	-0.32	1.01	--	75.24	2.92	219.61	56.04	--	--	98.25	1.31	0.45	1.75
3-2	1.1	2.48	0.92	2.89	22.21	2.44	0.45	-0.01	1.28	--	44.20	3.23	142.65	33.75	--	--	97.12	2.20	0.68	2.88
3-3	1.5	1.87	1.99	-0.10	2.59	2.08	1.65	-0.23	3.63	0.09	15.12	6.29	95.09	13.04	1.17	7.66	85.76	5.67	0.90	6.58
3-4	2.6	2.38	1.41	1.02	6.16	2.39	0.85	-0.18	2.33	0.02	19.17	5.03	99.07	16.44	0.24	1.38	92.97	4.72	0.94	5.65
3-5	3.0	-0.94	2.52	0.76	1.99	-1.29	2.21	0.15	1.13	1.23	13.17	3.12	42.78	10.38	12.74	52.82	43.04	3.14	1.01	4.15
3-6	4.6	-1.03	3.10	0.21	-0.03	-0.70	2.84	-0.14	0.52	0.97	17.58	4.18	73.39	14.18	13.74	47.51	49.03	2.79	0.67	3.46
3-7	6.1	-1.10	2.14	0.72	2.59	-1.39	1.92	0.13	1.09	1.22	37.90	1.92	72.76	24.92	30.27	53.87	44.35	1.17	0.61	1.78
3-8	7.6	1.97	1.53	1.48	6.66	1.73	0.97	0.30	3.05	0.01	18.61	4.06	75.62	14.93	0.14	0.84	92.94	4.99	1.23	6.22
3-9	9.1	3.19	1.95	0.80	1.68	2.59	1.69	0.48	1.22	0.002	3.33	9.74	32.43	3.02	0.01	0.17	75.00	22.52	2.31	24.84
3-10	10.4	4.14	2.46	0.69	0.61	3.05	2.17	0.65	1.15	--	2.07	3.90	8.09	1.65	--	--	62.27	30.04	7.70	37.74
3-11	11.0	3.01	1.55	1.39	4.67	2.59	1.06	0.55	2.71	--	6.36	7.62	48.45	5.63	--	--	84.91	13.34	1.75	15.10
BOREHOLE 6																				
6-1A	14.2	4.67	2.66	0.51	0.07	3.77	2.43	0.49	0.94	0.002	1.45	3.39	4.93	1.12	0.002	0.10	52.84	36.33	10.72	47.06
6-1	16.5	1.98	3.98	0.08	-0.04	2.47	4.15	-0.19	1.48	0.41	3.76	2.14	8.05	2.56	1.06	22.93	55.43	14.75	6.89	21.64
6-2	15.7	4.99	3.24	0.09	-0.20	4.97	3.19	0.03	1.22	0.08	0.89	2.81	2.50	0.66	0.05	2.92	38.46	43.25	15.37	58.63
6-3	17.1	5.71	2.20	0.59	0.41	5.03	1.94	0.52	1.72	--	0.21	5.54	1.18	0.18	--	--	15.23	71.82	12.96	84.78
6-4	18.3	2.67	1.89	1.35	4.19	2.29	1.20	0.30	2.52	0.004	12.48	2.23	27.85	8.62	0.04	0.36	89.28	7.16	3.21	10.36
6-5	21.3	2.91	1.88	0.68	4.26	2.63	0.99	0.31	3.70	0.02	10.21	3.05	31.16	7.69	0.18	2.01	86.72	8.49	2.78	11.28
6-6	22.9	4.69	2.28	0.77	0.73	3.46	1.90	0.87	1.20	0.001	1.77	3.71	6.57	1.39	0.002	0.08	58.19	32.88	8.86	41.73
6-7	25.9	5.14	2.63	0.53	-0.03	3.82	2.34	0.72	0.95	--	1.45	2.58	3.73	1.04	0.001	0.06	50.99	35.27	13.68	48.95
6-8	35.8	6.59	3.01	0.11	-0.73	6.14	2.99	0.20	0.72	--	0.96	1.23	1.18	0.53	--	--	34.67	36.05	29.28	65.33

BOREHOLE 4

Sample No.	Depth Below Surface (meters)	Moments φ				Graphical Statistics φ				Sediment Ratios						Sediment Size Percentages				
		M_1	M_2	M_3	M_4	Median	Sorting	Skewness	Kurtosis	Gravel/Sand	Sand/Silt	Silt/Clay	Sand/Clay	Sand/Mud	Gravel/Mud	Gravel	Sand	Silt	Clay	Mud
4-1	4.6	1.87	0.72	-1.11	3.63	1.95	0.51	-0.10	1.84	0.02	∞	3.00	∞	∞	3215.53	2.16	97.84	0.001	--	0.001
4-2	6.7	1.16	2.61	-0.59	1.48	1.89	1.99	-0.64	3.28	0.17	28.30	5.08	143.78	23.64	4.02	14.03	82.48	2.92	0.57	3.49
4-3	7.6	0.89	2.32	0.22	1.03	1.49	2.06	-0.54	0.89	0.29	29.14	3.69	89.26	19.03	5.55	21.70	74.39	3.08	0.83	3.91
4-4	10.7	1.38	1.65	1.02	5.10	1.41	1.03	-0.21	1.77	0.05	26.41	3.83	101.05	20.94	1.13	4.91	90.76	3.44	0.90	4.33
4-5	13.7	0.88	2.48	-0.20	1.25	1.53	2.02	-0.61	2.11	0.21	31.77	2.82	89.58	23.45	4.82	16.47	80.12	2.52	0.89	3.42
4-5A	15.2	1.70	1.53	1.48	7.80	1.59	0.74	-0.10	1.65	0.02	34.74	2.06	71.40	23.37	0.55	2.19	93.80	2.70	1.31	4.01
4-6	16.8	2.58	1.78	0.95	4.26	2.37	1.05	0.12	2.27	0.02	10.41	4.17	43.38	8.39	0.14	1.47	88.05	8.46	2.03	10.49
4-7	19.8	3.48	2.52	0.65	0.92	2.64	2.16	0.55	1.53	0.04	3.47	3.37	11.67	2.67	0.11	2.84	70.71	20.39	6.06	26.45
4-8	22.9	2.53	1.63	1.54	6.31	2.36	0.94	0.03	2.08	0.004	19.00	2.17	41.28	13.01	0.05	0.38	92.51	4.87	2.24	7.11
4-9	25.9	3.13	1.91	1.36	3.83	2.64	1.19	0.48	3.89	--	8.00	2.56	20.49	5.75	--	--	85.19	10.65	4.16	14.81
4-10	27.4	3.93	2.88	0.57	0.41	2.71	2.48	0.74	1.38	0.06	3.75	1.67	6.27	2.35	0.14	3.87	67.41	17.97	10.76	28.72
4-11	29.0	2.92	1.69	1.63	5.95	2.50	0.93	0.42	4.20	0.004	20.14	1.48	29.78	12.02	0.05	0.35	91.99	4.57	3.09	7.66
4-12	32.0	2.93	1.88	1.52	4.85	2.54	0.96	0.26	7.50	0.004	18.55	1.15	21.41	9.94	0.04	0.38	90.52	4.88	4.23	9.11
4-13	35.0	4.77	3.00	0.52	-0.16	3.20	2.74	0.79	0.99	--	3.02	1.26	3.81	1.69	0.001	0.02	62.74	20.76	16.48	37.24
4-14	34.7	7.70	3.22	-0.34	-0.34	7.79	3.48	-0.11	1.06	0.01	0.59	0.71	0.42	0.25	0.003	0.22	19.68	33.26	46.84	80.10
4-15	38.1	8.19	2.43	-0.39	0.43	7.66	2.17	0.35	0.94	0.04	0.07	1.26	0.09	0.04	0.002	0.16	3.68	53.58	42.58	96.16
4-16	41.1	7.68	2.24	0.02	-0.31	7.01	2.05	0.46	0.97	--	0.05	2.06	0.10	0.03	--	--	3.16	65.16	31.69	96.84
4-17	42.7	7.57	2.11	0.11	-0.18	6.92	1.97	0.43	1.26	--	0.03	2.54	0.07	0.02	--	--	1.90	70.35	27.75	98.10

BOREHOLE 5

Sample No.	Depth Below Surface (meters)	Moments ϕ				Graphical Statistics ϕ				Sediment Ratios						Sediment Size Percentages				
		M_1	M_2	M_3	M_4	Median	Sorting	Skewness	Kurtosis	Gravel/Sand	Sand/Silt	Silt/Clay	Sand/Clay	Sand/Mud	Gravel/Mud	Gravel	Sand	Silt	Clay	Mud
5-1	1.5	2.4479	0.7394	3.6522	39.0357	2.46	0.33	-0.47	1.08	--	20.97	0.85	186.93	101.26	--	--	99.02	0.45	.53	0.98
5-2	3.0	1.3538	1.7903	0.2774	2.8892	1.78	1.33	-0.60	1.52	0.13	35.28	3.43	120.92	27.31	3.63	11.38	85.50	2.42	.71	3.13
5-3	6.1	1.5362	1.4494	1.2686	7.9614	1.56	0.86	-0.26	1.38	0.03	42.55	2.11	89.86	28.88	0.86	2.80	93.95	2.21	1.05	3.25
5-3A	7.3	0.8069	1.4433	-0.2276	0.7746	1.10	1.33	-0.28	0.93	0.12	382.99	3.72	1424.82	301.85	35.45	10.48	89.23	0.23	0.06	0.30
5-4	9.1	2.9087	1.5668	1.3570	4.7825	2.55	1.03	0.35	1.95	--	8.80	5.77	55.80	7.50	--	--	88.24	10.02	1.74	11.76
5-5	13.7	2.0729	1.2861	1.5171	9.6899	2.02	0.73	-0.02	1.54	0.01	30.11	3.09	92.96	22.74	0.22	0.90	94.93	3.15	1.02	4.17
5-6	14.5	4.0737	2.8556	0.6355	0.1690	2.73	2.60	0.73	0.94	--	3.97	1.69	6.73	2.50	--	--	71.40	17.48	10.62	28.60
5-7	16.8	1.7473	1.2958	0.4363	7.7040	1.85	0.72	-0.24	2.12	0.03	68.18	2.70	183.82	49.74	1.70	3.23	94.86	1.39	0.52	1.91
5-8	19.5	3.2427	1.8629	1.0855	2.7301	2.75	1.53	0.51	2.08	--	5.17	5.40	27.96	4.37	--	--	81.37	15.73	2.91	18.64
5-9	20.4	3.7070	2.1404	0.9102	1.4822	2.92	1.71	0.64	1.32	--	3.46	4.56	15.76	2.84	--	--	73.93	21.38	4.69	26.07
5-10	22.9	3.05	2.12	1.19	2.74	2.46	1.35	0.48	3.91	--	7.99	2.28	18.23	5.56	--	--	84.75	10.60	4.65	15.25
5-11	22.5	4.23	2.77	0.59	0.19	2.92	2.33	0.63	0.99	--	2.39	2.51	6.00	1.71	--	--	63.09	26.39	10.52	36.91
5-12	25.9	2.54	1.74	1.40	4.74	2.17	1.16	0.32	2.74	--	11.42	3.44	39.29	8.85	--	--	89.85	7.87	2.29	10.16
5-13	25.0	4.70	2.94	0.44	-0.19	3.55	2.77	0.51	0.91	--	1.75	2.37	4.15	1.23	--	--	55.19	31.52	13.29	44.81
5-13A	29.0	5.55	3.04	0.25	-0.45	4.93	2.81	0.34	0.83	0.01	1.11	1.97	2.19	0.74	0.01	0.35	42.32	38.04	19.30	57.33
5-14	29.0	6.79	2.79	0.07	-0.58	6.57	2.93	0.07	1.08	--	0.33	1.97	0.66	0.22	--	--	18.07	54.36	27.57	81.93
5-15	32.0	4.72	2.56	0.60	0.21	3.41	2.24	0.72	1.05	--	1.63	3.16	5.14	1.24	--	--	55.26	33.99	10.75	44.74
5-16	33.4	5.25	2.75	0.49	-0.17	4.54	2.54	0.46	0.95	--	1.18	2.41	2.84	0.83	--	--	45.47	38.54	16.00	54.54
5-17	34.7	3.16	2.12	1.06	2.48	2.71	1.55	0.30	2.57	--	7.09	2.54	18.27	5.16	0.01	0.12	83.66	11.64	4.58	16.22
5-18	38.1	2.69	1.66	1.43	5.18	2.43	1.10	0.21	2.14	--	13.51	3.00	40.57	10.14	--	--	91.02	6.74	2.24	8.98

APPENDIX B. BOREHOLE MEGAFAUNA

BOREHOLE 2

Fauna	Depth Below Surface		Sediment Sample No.
	meters	feet	
Bivalve: Macoma secta (Conrad)	8.2	27	2-5
Bivalve: Tresus sp.	16.8	55	2-12
Bivalves: Clinocardium nuttalli (Conrad), Macoma secta (Conrad)	26.5	87	
Bivalves: Clinocardium nuttalli (Conrad), Macoma sp. ?, Protothaca staminea (Conrad)	25.9-27.4	85-90	
Gastropod: Nassarius sp.	27.4	90	2-21
Gastropod: Mitrella carinata (Sowerby)	28	92	2-22
Bivalves: Clinocardium nuttalli (Conrad), Modiolus sp. ?	30.5	100	2-25
Bivalve: Macoma cf. M. secta (Conrad)	31.1	102	
Gastropod: Nassarius mendicus cooperi (Forbes)			
Bivalve: Macoma cf. M. nasuta (Conrad)	33.5	110	2-29
In addition to fauna listed above, the following were identified from uncertain depths.	---	---	
Bivalves: Cryptomya californica (Conrad), Tresus sp.			
Gastropod: Olivella biplicata (Sowerby)			
Bryozoans			

BOREHOLE 3 & 6

Fauna	Depth Below Surface		Sediment
	meters	feet	Sample No.
Gastropod: Mitrella carinata (Sowerby)	0-9.8	0-32	
Bivalve: Protothaca staminea (Conrad)	6.1	20	3-7
Gastropods: Nucella sp. Olivella sp. Searlesia sp. ?			
Barnacle: Balanus sp.			
Gastropods: Diodora sp. ? Nucella sp.	6.1-7.3	20-24	
Bivalves: Macoma nasuta (Conrad) Tresus sp. cf. T. capax (Gould)	7.9-8.2	26-27	3-8
Bivalve: Tresus sp.	8.2-9.1	27-30	3-9
Bivalves: Macoma nasuta (Conrad) Protothaca staminea (Conrad) Tresus sp.	8.2-10.4	27-34	
Bryozoans			
Bivalve: Clinocardium nuttalli (Conrad)	14.0	46	6-1A
Bivalves: Clinocardium nuttalli (Conrad) Macoma nasuta (Conrad) Protothaca staminea (Conrad) Tresus sp. ? Undetermined thin-shelled taxon	15.2	50	
Bivalve: Macoma cf. M. nasuta (Conrad)	15.8	52	6-2

BOREHOLE 3 & 6 (cont.)

Fauna	Depth Below Surface		Sediment
	meters	feet	Sample No.
Bivalve: Macoma nasuta (Conrad)	16.5-16.6	54-54.5	6-1
Bryozoans			
Bivalves: Macoma nasuta (Conrad) Saxidomus giganteus (Deshayes)	17.1	56	6-3
Bryozoans			
Bivalves: Macoma sp. Ostrea cf. O. lurida Carpenter Tresus sp.	19.5-19.8	64-65	
Bryozoans			
Echinoid spines			
Gastropod: Nucella sp.	21.0	69	6-5
In addition to fauna listed above, the following were identified from uncertain depths.	---	---	
Bivalves: Cryptomya californica (Conrad) Hinnites multirugosus (Gale) Macoma secta (Conrad) Mytilus sp. ? Penitella sp. ? Petricola carditoides (Conrad)			
Gastropods: Acanthina spirata (Blainville) Nucella lamellosa (Gmelin) Olivella biplicata (Sowerby)			

BOREHOLE 4

Fauna	Depth Below Surface		Sediment
	meters	feet	Sample No.
Bivalves: Macoma nasuta (Conrad) Protothaca staminea (Conrad) **Gastropods:** Olivella biplicata (Sowerby) Searlesia dira (Reeve)	9.4-9.8	31-32	
Bivalves: Pholadid Protothaca staminea (Conrad) **Gastropod:** Nucella lamellosa (Gmelin)	12.5-12.8	41-42	
Bivalves: Macoma nasuta (Conrad) Protothaca staminea (Conrad)	16.2-16.8	53-55	4-6
Bivalves: Macoma sp. Protothaca staminea (Conrad)	17.7	58	
Bivalves: Clinocardium cf. C. nuttalli (Conrad) Macoma nasuta (Conrad) **Gastropod:** Mitrella carinata (Sowerby) **Barnacle:** Balanus sp. ?	19.5-19.8	64-65	4-7
Bivalve: Macoma nasuta (Conrad)	20.6	67.5	
Bivalves: Clinocardium cf. C. nuttalli (Conrad) Macoma sp. Protothaca staminea (Conrad)	20.4-21.9	67-72	
Bivalve: Cryptomya californica (Conrad)	21.3	70	

BOREHOLE 4 (cont.)

Fauna	Depth Below Surface		Sediment
	meters	feet	Sample No.
Bivalves: *Clinocardium nuttalli* (Conrad) *Macoma nasuta* (Conrad) *Protothaca staminea* (Conrad)	22.9-23.2	75-76	4-8
Bivalves: *Macoma* sp. *Macoma* sp. -- fossil *Mytilid*	24.1	79	
Bivalves: *Clinocardium* cf. *C. nuttalli* (Conrad) *Macoma* sp. *Macoma* sp. -- fossil *Mytilus* sp. ? *Protothaca staminea* (Conrad)	25.3-25.6	83-84	
Barnacle: *Balanus* sp.			
Bivalve: *Macoma* cf. *M. nasuta* (Conrad)	25.9	85	4-9
Bivalve: *Macoma* cf. *M. secta* (Conrad)	26.8-27.1	88-89	4-10
Bivalves: *Cryptomya californica* (Conrad) *Macoma nasuta* (Conrad) *Protothaca staminea* (Conrad)	28.7	94	
Bivalves: *Clinocardium* cf. *C. nuttalli* (Conrad) *Macoma* sp.	29.6	97	
Gastropod: *Mitrella carinata* (Sowerby)			
Bivalves: *Cryptomya californica* (Conrad) *Protothaca staminea* (Conrad)	29.9-30.5	98-100	

BOREHOLE 4 (cont.)

Fauna	Depth Below Surface		Sediment
	meters	feet	Sample No.
Bivalve: *Macoma nasuta* (Conrad)	31.1	102	
Bivalve: *Macoma nasuta* (Conrad) -- fossil	31.2-31.7	102.5-104	
Bivalves: *Cryptomya californica* (Conrad) *Macoma nasuta* (Conrad)	32	105	4-12
Bivalves: *Ostrea lurida* Carpenter *Protothaca staminea* (Conrad)	34.4	113	
Bivalves: *Ostrea lurida* Carpenter *Mytilus* or *Modiolus*	34.7	114	4-14
In addition to fauna listed above, the following were identified from uncertain depths.	---	---	
Bivalves: *Hinnites* sp. *Macoma inquinata* (Deshayes) *Saxidomus* cf. *S. giganteus* (Deshayes) *Tellina bodegensis* (Hinds) *Tresus* sp.			
Echinoid: *Dendraster* sp. ?			

BOREHOLE 5

Fauna	Depth Below Surface		Sediment Sample No.
	meters	feet	
Bivalves: Protothaca staminea (Conrad)	5.6	18.5	
Bivalve: Hinnites sp. ?	12.6	41.5	
Gastropod: Tegula sp. ?			
Bivalves: Macoma nasuta (Conrad) Tresus sp.	16.5-16.6	54-54.5	5-7
Bivalve: Protothaca staminea (Conrad)	17.7	58	
Bivalves: Clinocardium cf. C. nuttalli (Conrad) Macoma sp. Protothaca staminea (Conrad) Transenella sp.	18.9-19.4	62-63.5	5-8
Bivalves: Cryptomya californica (Conrad) Macoma sp.	20.4	67	5-9
Bivalve: Clinocardium cf. C. nuttalli (Conrad)	22.4-22.6	73.5-74	5-11
Gastropod: Mitrella carinata (Sowerby)	22.7	74.5	5-11
Gastropods: Nassarius mendicus cooperi (Forbes) Searlesia cf. S. dira (Reeve)	23.5	77	
Bivalves: Clinocardium sp. ? Macoma nasuta (Conrad) Mytilid Protothaca staminea (Conrad)	25.9	85	5-12
Bivalves: Mytilus sp. Protothaca staminea (Conrad)	27.1	89	

BOREHOLE 5 (cont.)

Fauna	Depth Below Surface		Sediment Sample No.
	meters	feet	
Bivalve: Clinocardium cf. C. nuttalli (Conrad)	29	95	5-14
Crustacean fragments			
Gastropod: Odostomia sp.	31.1	102	
Bivalves: Macoma inquinata (Deshayes) Mytilus sp. ?	34.1-34.3	112-112.5	
Gastropod: Olivella biplicata (Sowerby)			
In addition to fauna listed above, the following were identified from uncertain depths.	---	---	
Bivalves: Petricola carditoides (Conrad) Pholadid Platyodon sp. Saxidomus cf. S. giganteus (Deshayes)			
Gastropods: Diodora aspera (Rathke) Lacuna cf. L. solidula compacta (Carpenter) Nucella lamellosa (Gmelin)			
Barnacle: Balanus sp.			

Identifications by Warren O. Addicott, U. S. Geological Survey, Menlo Park, California, and Joel R. Bergquist.

APPENDIX C. Coordinates and Elevations of Tops of Boreholes and Cores

NO.[1]	CORE IDENTIFICATION NUMBER	LATITUDE	LONGITUDE	UTM COORDINATES		ELEVATION RELATIVE TO MSL (feet)
				Easting	Northing	
1	8-1-74-4	37 55 57.3335	122 41 45.1789	526725.778	4198174.164	
2	6-76	37 55 53.6505	122 41 42.3229	526795.867	4198060.884	
3	9-6-75-4	37 55 46.7350	122 41 28.3733	527137.103	4197848.877	-2.02
4	9-6-75-3	37 55 47.4431	122 41 26.6905	527178.110	4197870.834	-1.88
5	9-6-75-2	37 55 48.0823	122 41 25.1961	527214.527	4197890.658	-1.82
6	9-6-75-1	37 55 48.7318	122 41 23.7894	527248.802	4197910.787	-1.82
7	8-24-75-1	37 55 39.3454	122 40 58.8203	527859.328	4197623.556	
8	8-1-74-3	Location not recoverable				
9	8-1-74-1	37 55 24.4480	122 40 58.5087	527868.499	4197164.458	
10	9-20-75-1	37 54 55.0539	122 41 28.5370	527138.382	4196256.102	+9 (est.)
11	9-6-75-5	37 54 56.0745	122 41 25.3872	527215.186	4196287.809	+5.94
12	9-6-75-6	37 54 57.2044	122 41 22.3873	527288.317	4196322.875	+4.11
13	9-9-75-3	37 55 7.8532	122 40 51.1860	528049.029	4196653.078	+1.51
14	9-9-75-2	37 55 10.4259	122 40 43.4667	528237.224	4196733.570	+1.65
15	9-9-75-1	37 55 10.6321	122 40 42.8642	528251.912	4196739.973	+1.31
16	2-21-76-2	37 54 45.6665	122 40 3.5511	529214.504	4195973.923	
17	2-21-76-1	37 54 46.7381	122 40 4.1351	529200.127	4196006.897	
18	2-21-76-3	37 54 44.0699	122 40 2.9570	529229.185	4195924.770	
19	Borehole 3&6	37 54 28.2695	122 40 39.4928	528338.742	4195434.684	+8.08
20	Borehole 5	37 54 27.4240	122 40 25.8264	528672.557	4195409.789	+6.44
21	Borehole 2	37 54 28.6596	122 39 54.2077	529444.530	4195450.605	+9.21
22	Borehole 4	37 54 15.8087	122 39 7.8985	530576.848	4195058.693	+7.39

[1] Numbers correspond to locations on figure 21.

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