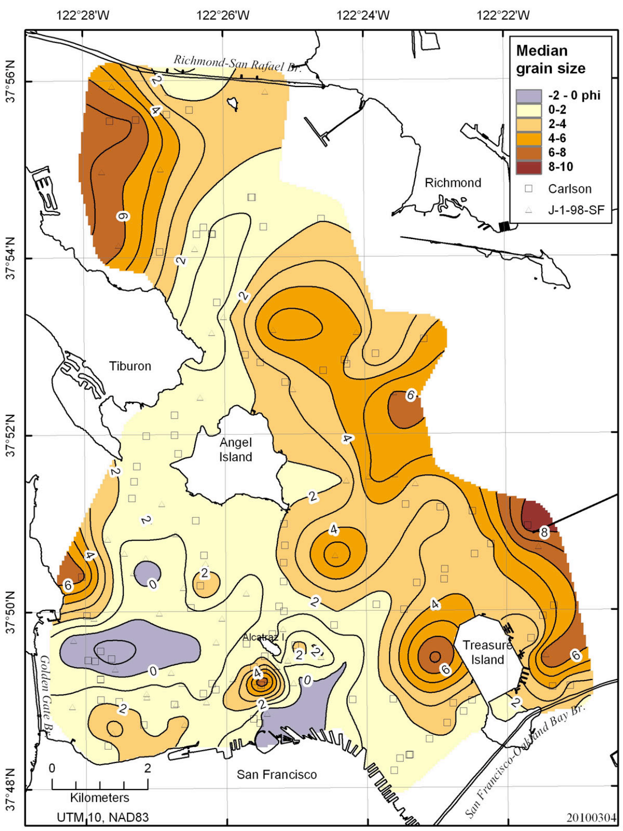
Estuarine Sedimentation, Sediment Character, and Foraminiferal Distribution in Central San Francisco Bay, California

By John L. Chin, Donald L. Woodrow, Mary McGann, Florence L. Wong,
Theresa Fregoso, and Bruce E. Jaffe



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Cover illustration: Sediment grain size distribution, central San Francisco Bay (Woodrow and others, this study).

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Summary

Central San Francisco Bay is the deepest subembayment in the San Francisco Bay estuary and hence has the largest water volume of any of the subembayments. It also has the strongest tidal currents and the coarsest sediment within the estuary. Tidal currents are strongest over the west-central part of central bay and, correspondingly, this area is dominated by sand-size sediment (Figure 0-1). Much of the area east of a line from Angel Island to Alcatraz Island is characterized by muddy sand to sandy mud, and the area to the west of this line is sandy. The sand-size sediment over west-central bay furthermore is molded by the energetic tidal currents into bedforms of varying sizes and wavelengths. Bedforms typically occur in water depths of 15-25 m.

High resolution bathymetry (multibeam) from 1997 and 2008 allow for subdivision of the west-central bayfloor into four basic types based on morphologic expression: featureless, sand waves, disrupted/man-altered, and bedrock knobs. Featureless and sand-wave morphologies dominate the bayfloor of west-central bay. Disrupted bayfloor has a direct association with areas that are undergoing alteration due to human activities, such as sand-mining lease areas, dredging, and disposal of dredge spoils.

Change detection analysis, comparing the 1997 and 2008 multibeam data sets, shows that significant change has occurred in west-central bay during the roughly 10 years between surveys. The surveyed area lost about 5.45 million m^3 of sediment during the decade. Sand-mining lease areas within west-central bay lost 6.77 million m^3 as the bayfloor deepened. Nonlease areas gained 1.32 million m^3 of sediment as the bayfloor shallowed slightly outside of sand-mining lease areas. Furthermore, bedform asymmetry did not change significantly, but some bedforms did migrate some tens of meters.

Gravity cores show that the area east of Angel and Alcatraz Islands is floored by clayey silts or silty sand whereas the area to the west of the islands is floored dominantly by sand- to coarse sand-sized sediment. Sandy areas also include Raccoon Strait, off Point Tiburon, and on the subtidal Alcatraz, Point Knox, and Presidio Shoals. Drab-colored silty clays are the dominant sediment observed in gravity cores from central bay. Their dominance along the length of the core suggests that silty clays have been deposited consistently over much of this subembayment for the time period covered by the recovered sediments (Woodrow and others, this report). Stratification types include weakly-defined laminae, 1-3 mm thick. Few examples of horizontal lamination in very fine sand or silt were observed. Cross lamination, including ripples, was observed in seven cores. Erosional surfaces were evident in almost every core where x-radiographs were available (they are very difficult to observe visually). Minor cut-and-fill structures also were noted in three cores and inclined strata were observed in three cores.

Textural patterns in central bay indicate that silts and clays dominate the shallow water areas and margins of the bay. Sand dominates the tidal channel just east of Angel and Alcatraz Islands and to the west of the islands to the Golden Gate (Woodrow and others, this report). The pattern of sand-sized sediment, as determined by particle-size analysis, suggests that sand movement is easterly from the west-central part of the bay. A second pattern of sand movement is to the south from the southwestern extremity of San Pablo Bay (boundary approximated by the location of the Richmond-San Rafael Bridge).

Age dates for central bay sediment samples were obtained by carbon-14 radiometric age dating. Age dates were determined from shell material that was interpreted to be largely in-place (not transported). Age dates subsequently were reservoir corrected and then

converted to calendar years. Sediments sampled from central bay cores range in age from 330 to 4,155 years before present.

Foraminiferal distribution in the San Francisco Bay estuary is fairly well documented except for central bay. This study fills the data gap for both natural and introduced species of benthic foraminifera. Thirty-five species of arenaceous and calcareous benthic foraminiferal fauna were identified in 55 grab samples obtained in central bay in 1998. This includes the invasive Japanese species *Trochamina hadai*, thought to have been first introduced into San Francisco Bay in the early 1980s (McGann, this report). Four assemblages of foraminifers were recognized based on cluster analysis: shallow east bay, intermediate east bay, deep western bay estuarine, and deep western bay marine. The foraminiferal distributions verify that west central bay is the most oceanically influenced region of the estuary. Foraminifers also document sediment transport by the relocation of species from their natural habitat. For example, *T. hadai* dominated (68-98 percent) the benthic fauna of shallow-water depths (shallow east bay assemblage) of central bay. The occurrence of this invasive species is similar to that in its home waters in Japan and along the East Pacific seaboard.

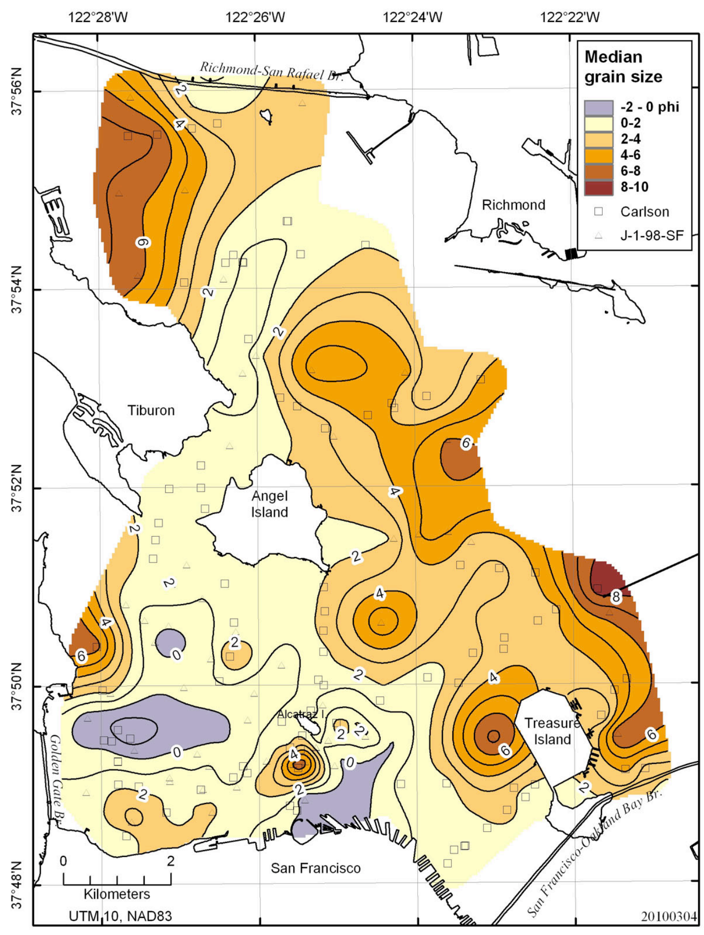

Figure 0-1. Sediment grain-size distribution, central San Francisco Bay, California (Woodrow and others, this study).

Chapter I. Estuarine Sedimentation in Central San Francisco Bay, California

By John L. Chin, Donald L. Woodrow, Mary McGann, Florence L. Wong, and Bruce E. Jaffe

Introduction

San Francisco Bay is one of the largest estuaries on the United States Pacific Coast, and it consists of several subembayments: Suisun Bay, San Pablo Bay, central bay, and south bay (Figure 1-1). A narrow body of water, Carquinez Strait, connects Suisun Bay to San Pablo Bay. Each subembayment is characterized by a central area of open water surrounded by intertidal and subtidal flats and tidal marshes. San Francisco Bay and the contiguous Sacramento-San Joaquin Delta encompass about 4,100 km^2 (1,600 mi^2) and is the outlet of a major watershed draining more than 40 percent of the land area of the State of California (Figure 1-1).

Central San Francisco Bay's location adjacent to a major urban population center of some 7 million people and to two major ports makes it an important natural resource. We arbitrarily establish the geographic boundaries of the central bay study area to coincide with the major bridges that cross its waters—the Golden Gate Bridge to the west, the San Francisco-Oakland Bay Bridge to the south, and the Richmond-San Rafael Bridge to the north (Figure 1-2). Richardson Bay, a small shallow subembayment, occurs on the northwestern margin of central bay. The Golden Gate, at the western terminus of central bay, is the only outlet of the San Francisco Bay estuary to the Pacific Ocean. Tidal flow through the Golden Gate into the San Francisco Bay estuary generates a tidal prism of 2×10^9 m^3 (528 billion gallons) with tidal currents that typically exceed 2.5 m/s (Barnard and others, 2006). Tides in San Francisco Bay are mixed and semidiurnal with uneven highs (2) and lows (2) each day (Conomos, 1979). They vary in range from 0.6 m during the weakest neap tides to 1.8 m during the strongest spring tides.

The average water depth of central bay is 11 m Mean Lower Low Water (MLLW) compared to an average water depth of 6 m MLLW for the entire San Francisco Bay, and is about three times that of south and north bays. Due to its greater average water depth, central bay also has the largest water volume in San Francisco Bay, even though its surface area is less than half that of south bay.

Central bay has been the subject of a number of previous investigations that include Gilbert (1917), Carlson and McCulloch (1970), Carlson and others (1970), Conomos (1979), Rubin and McCulloch (1979), Nichols and others (1986), Chin and Clifton (1990), Clifton and others (1991), Chin and others (1997), Chin and others (1998), Carlson and others (2000), and Chin and others (2004).

The intent of this report is to describe the morphology of the bayfloor and the physical sedimentary features observed in gravity cores collected in central San Francisco Bay, and to discuss the distribution of benthic foraminifers obtained from a suite of surface grab samples collected in 1998 and how these characterize Central San Francisco Bay sediments.

Methods

This report utilizes a variety of data types collected by the U.S. Geological Survey (USGS). The primary dataset consists of gravity cores collected in 1990, 1991 and 1996 (U.S. Geological Survey, J-2-90-SF, J-2-91-SF, J-5-96-SF, J-6-96-SF). Secondly, we employ surface grab samples collected in 1998, multibeam bathymetry collected in 1997 and 2008 (U.S. Geological Survey, C-1-97-SF, C-2-97-SF, J-1-98-SF; Kvitek, 2008), and sidescan sonar profiles collected in 1997 and 1998 (U.S. Geological Survey, J-2-97-SF, J-1-98-SF).

Gravity cores were collected in 1990-1991 using the *RV Johnston* (Anima and others, 2005; U.S. Geological Survey, J-2-90-SF, J-2-91-SF). Navigation was acquired using radar fixes. A gravity core was fitted with a 272 kg (600 lb) weight and core barrels from 1.2-6.4 m (4-20 ft) in length with polybuterate core liners and a core catcher. Once the core was recovered, the polybuterate core liner was removed, capped, and stored aboard ship. Cores were subsequently stored at the USGS Core Facility (Menlo Park, California) in a refrigerator at 39° F. In 2007-2008, cores were spilt longitudinally into halves, visually described, and digitally photographed (Woodrow and others, this report). Some cores experienced dessication, fracturing, shortening, and geochemical changes (such as color alteration and crystal formation) between collection (1990, 1991) and description (2007-2008). A subset of the cores was x-radiographed and subsampled for analyses of sediment grain size down-core (Woodrow and others, this report).

Visual descriptions of the cores delineated texture, color, physical and biologic structures, and deformation in the logging process. Texture down-core was estimated visually using a 10x hand lens by comparing grain size in the core to a grain-size card. Visual descriptions of grain size are fairly accurate except at the boundary between size classes (very fine sand/coarse silt; fine silt/clay) where some error may occur. Textural analyses were conducted on a limited number of the cores (Woodrow and others, this report). Colors were determined by comparison with a Munsell Soil Color Chart.

Surface-sediment grab samples (U.S. Geological Survey, J-5-97-SF, J-8-97-SF) and sidescan sonar profiles (U.S. Geological Survey, J-2-97-SF, J-1-98-SF) were collected using the *RV Johnston* in 1997 and 1998. Navigation on all cruises utilized DGPS. Textural analyses were conducted on 56 surficial sediment samples. The textural results are reported in greater detail in Watt (2003). Supporting data include 200 kHz bathymetry profiles and 3.5 kHz subbottom profiles. Results from the surface-sediment texture and sidescan sonar analyses were used to support interpretations based on the gravity cores and multibeam imagery.

Morphology of the Bayfloor

Central bay is characterized by a deep western area with shallow subtidal to intertidal flats to the east and northeast of the deep area (Figures 1-3, 1-4). Raccoon Strait is a tidal channel situated between Angel Island and the Tiburon Peninsula (Figures 1-3, 1-4). This deep tidal channel, >20 m water depth for much of its length, terminates to the northeast as it merges with a tidal channel that transects the bay, trending north-south, east of Angel Island and Alcatraz Island (Figures 1-3, 1-4). To the southwest, Raccoon Strait merges with another unnamed tidal channel that occurs between the scarp marking the mouth of Richardson Bay (west) and a subtidal levee on the western margin of Point Knox Shoal (Figures 1-3, 1-4). This unnamed channel averages >20 m deep and becomes deeper as it trends southwest where it merges with the Golden Gate.

East of Angel Island and Alcatraz Island a broad tidal channel bisects central bay all the way from the San Francisco-Oakland Bay Bridge north to the Richmond-San Rafael Bridge (Figures 1-2, 1-3). This tidal channel coincides with the shipping channel/navigation lane that transects the eastern portion of central bay. It is roughly delimited by waters deeper than about 9.4 m. Its western margin is ill-defined because of the deep subtidal areas and morphologic features of the western part of central bay. This includes Angel and Alcatraz Islands, the subtidal area north of the San Francisco waterfront, and Raccoon Strait. The eastern margin of this channel consists of the broad subtidal and intertidal tidal flats that occur between the tidal channel and the Oakland-to-Richmond shoreline (Figures 1-2, 1-3). In places this subtidal to intertidal flat is 1.8 km wide. North and east of the Tiburon Peninsula the through-going tidal channel bisects subtidal to intertidal tidal flats that occur on both its eastern and western margins (Figures 1-2, 1-3). A small subtidal shoal splits this tidal channel into eastern (ship channel to Port of Richmond) and western portions. The tidal channel continues north and merges with the main tidal channel in San Pablo Bay, San Pablo Strait.

West-central bay has the most diverse morphology and is the deepest water area of central bay. The bayfloor is characterized by deep areas (20-30 m or more) east of the Golden Gate, southeast of Angel Island (Point Blunt), and in Raccoon Strait (Figures 1-3, 1-4). Subtidal shoals (5-20 m deep) occur north of the San Francisco waterfront east to Alcatraz Island (Alcatraz and Presidio Shoals) and southwest of Angel Island (Point Knox Shoal). Alcatraz disposal site, immediately southwest of Alcatraz Island, occurs in 11-25 m water depth and is an anthropogenic feature resulting from the disposal of dredge materials (Chin and others, 2004). Below the Golden Gate Bridge, the water depth reaches 113 m based on 2008 multibeam data (Barnard and others, 2006). Bedrock knobs break through the sediment cover (Chin and others, 2004).

Multibeam imagery collected during 1997 and 2008 surveys shows the morphology of the bayfloor and allows for measurements of net change in the sediment surface during the roughly 10 years between surveys. The shaded relief image of multibeam bathymetry (Figure 1-4) shows that there are four types of morphologic bayfloor patterns present in west-central bay: (1) featureless, (2) sand waves, (3) disrupted/man-altered, and (4) bedrock knobs (Chin and others, 2004). The theoretical vertical resolution of the multibeam systems used in 1997 and 2008 is 10 cm or better. Thus, features smaller than about 10 cm likely would appear flat on the imagery and be mapped in the featureless category. Some natural bed features (ripples and small sand waves) and some man-modified features that are <10 cm in height would be mapped as "featureless" owing to the minimum vertical resolution of the sound systems used.

Featureless bayfloor appears on the shaded-relief imagery as generally smooth, flat to gently sloping, and largely devoid of any recognizable physical features (Figure 1-4). Regions of the bayfloor that are considered featureless include the topographic low southeast of Point Blunt on Angel Island, parts of the bayfloor north of the San Francisco waterfront, the unnamed tidal/ship channel east of Angel Island transecting the bay from the San Francisco-Oakland Bay Bridge to the Richmond-San Rafael

Bridge, and much of the area between the southwestern terminus of Raccoon Strait and the Golden Gate. Topographic depressions off Point Blunt, adjacent to Point Knox Shoal and the mouth of Richardson Bay, off Points Campbell and Stuart (Angel Island) also typically are featureless (Figure 1-4).

Most bedforms occur in about 15-25 m of water depth (Barnard and others, in press). Sand waves and smaller ripples occur primarily on the central bay shoals (Alcatraz, Presidio, and Point Knox), in Raccoon Strait, and in the adjacent unnamed tidal/shipping channel. Sand waves on Point Knox Shoal (Figure 1-4) are about 1-2 m in height and 30-60 m in wavelength, while those on Alcatraz and Presidio Shoals also are 1-2 m in height, but 25-90 m in wavelength. The largest sand waves inside the bay occur in Raccoon Strait and east of the Tiburon Peninsula where heights range from 1-2 m and have wavelengths similar to other areas in central bay. Sand waves within the bay generally are less than about 2 m in height. Sand waves in the Golden Gate and outside the Gate are larger still than any observed inside the bay but are outside the scope of this report (Rubin and McCulloch, 1979; Barnard and others, 2006).

Central bay has been the locus of anthropogenic activity since the 1800s and parts of the bayfloor have been modified significantly as a result (Chin and others, 2004). Figure 1-4 shows areas of the central bay bayfloor that have been modified historically and are referred to as the disrupted area. Additionally, sand mining lease areas on Point Knox, Alcatraz, and Presidio Shoals (Figure 1-5) continue to be modified as sand is extracted by hopper dredges (Chin and others, 2004). Alcatraz disposal site, immediately southwest of Alcatraz Island (Figure 1-5), is a man-made topographic mound that rises to within about 11 m of sea level (Chin and others, 2004).

Bedrock knobs that break through the sediment surface and outcrop on the bayfloor are the fourth morphologic bayfloor category. The most prominent knobs in central bay are Harding Rock, Shag Rock, Arch Rock, Blossom Rock, Anita Rock and Red Rock (Figure 1-4). These knobs are composed of Franciscan Complex bedrock similar to the surrounding Angel and Alcatraz Islands, as well as Marin and Tiburon Peninsulas. The nominal water depth at the shallowest top of the central bay bedrock knobs is 12 m (Chin and others, 2004).

Depth-change analysis of the 1997 and 2008 multibeam surveys reveal significant changes in the bayfloor during the roughly 10 year interval (P.L. Barnard, written commun., Aug. 2009). The two multibeam systems were able to resolve bedform wavelengths greater than 4 m and heights greater than 2 cm. The analysis shows that the entire area covered by the two surveys (Figure 1-4) lost 5.45 million m^3 of sediment in the 10-year period between surveys. Barnard calculated the sand mining lease areas (Figure 1-5) lost 6.77 million $m^{3,}$ while the nonlease areas gained 1.32 million m^3 of sediment. The loss of sediment within the sand-mining lease areas would appear to correspond to known sand-mining aggregate operations in west-central San Francisco Bay. Barnard concludes from his analysis that there is no systematic preferred transport direction and an insignificant sediment supply (from recirculation of sediment) within central bay. Furthermore, Barnard and others (2007), used numerical modeling to show that total net sediment transport (suspended and bedload) across the Golden Gate is about 25 percent greater in the ebb direction. This implies that sediment removed from the bay by dredging and sand mining could reduce the coastal sediment supply, a trend at least partially supported by the loss of more than 90 million m^3 of sediment from the mouth of San Francisco Bay during the last 50 years (Barnard and others, 2006). Analysis of the bedforms inside and outside the bay indicates that average-sized features inside the bay are 14 percent more sediment starved than those outside the bay—suggesting that the sediment supply to bedforms within the bay is reduced relative to that for bedforms outside the bay (Barnard and others, in press).

Analysis of the two multibeam data sets shows that during the 10-year period between surveys the asymmetry of the bedforms and their shape did not change significantly. The bedforms in the primary fields (Point Knox, Presidio, Alcatraz Shoals, and in Raccoon Strait) did show migration both short and long term. In 2.6 months the bedforms migrated 10 m seaward, and during the time span between the two surveys migrated 62 m (Barnard and others, in press).

Acknowledgments

We would like to thank the following for their contributions to this investigation: Paul Carlson (retired, formerly of USGS), the staff of the USGS Marine Facility, and Steve Watt. We would also like to thank Mike Torresan and Peter Dartnell (both USGS) for their technical reviews of this report.

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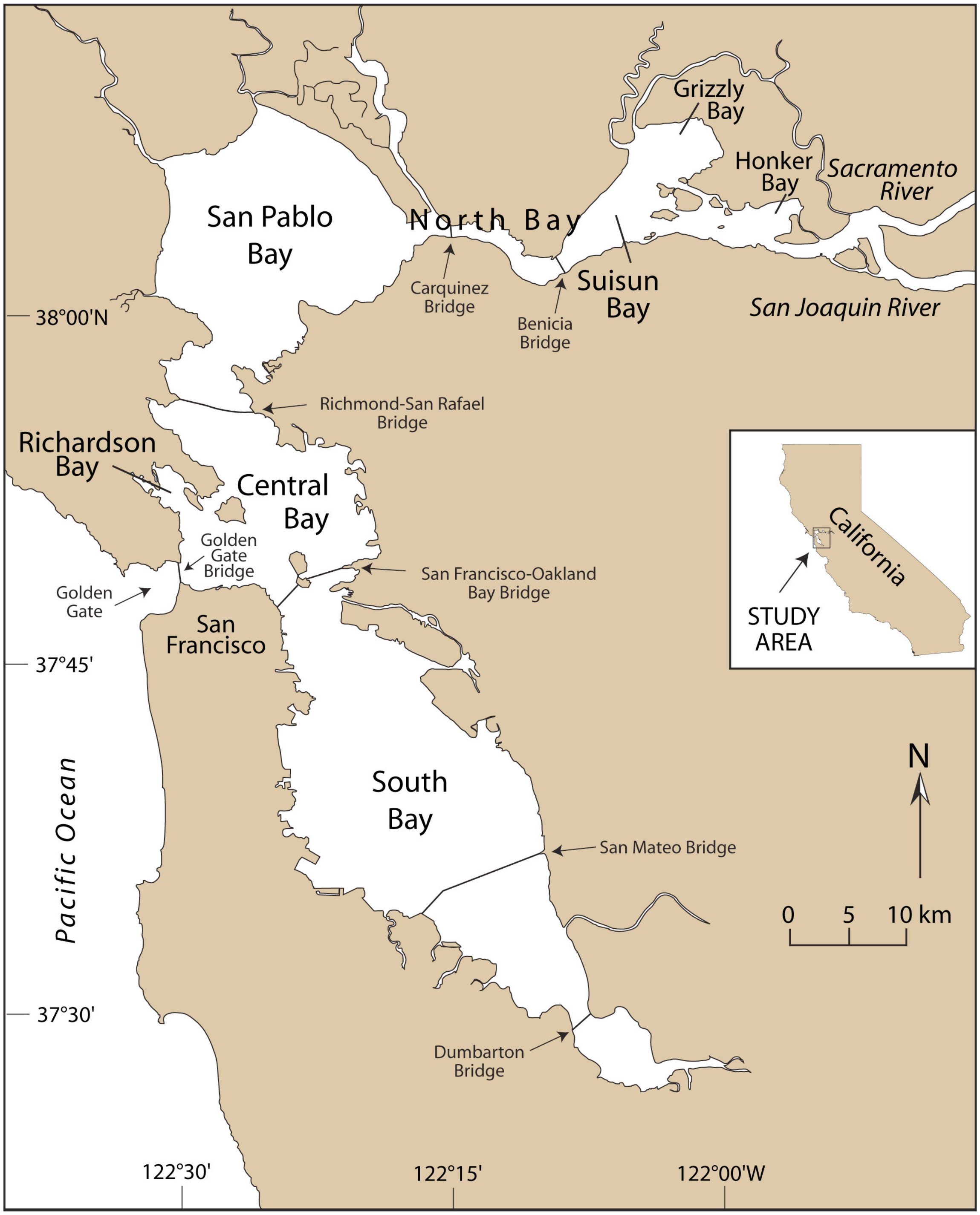

Figure 1-1. Regional location map of San Francisco Bay with inset of California and three subembayments: north bay (San Pablo Bay, Suisun Bay, Grizzly Bay, and Honker Bay), central bay (including Richardson Bay), and south bay.

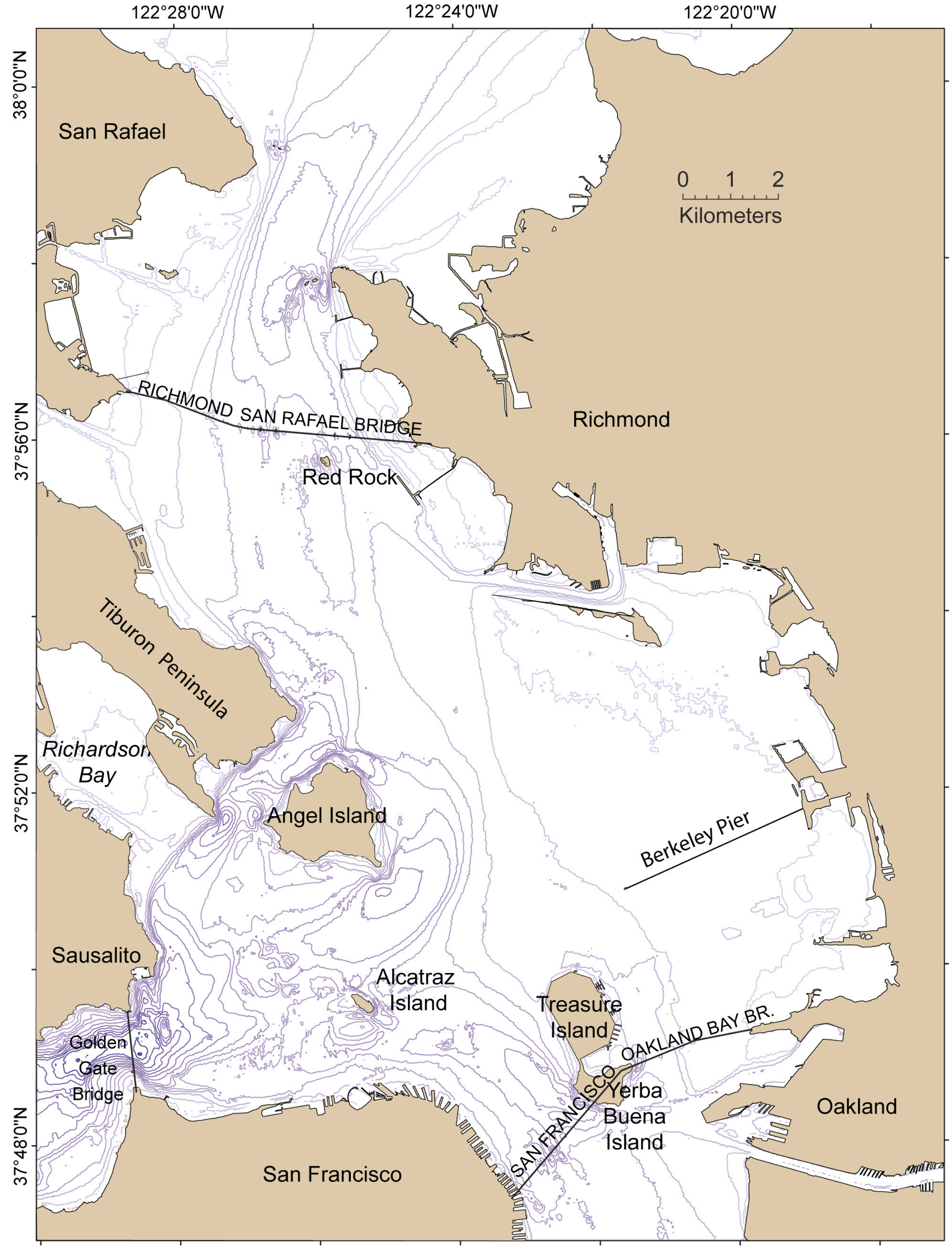

Figure 1-2. Map of central San Francisco Bay, California, showing key geographic features and bridges.

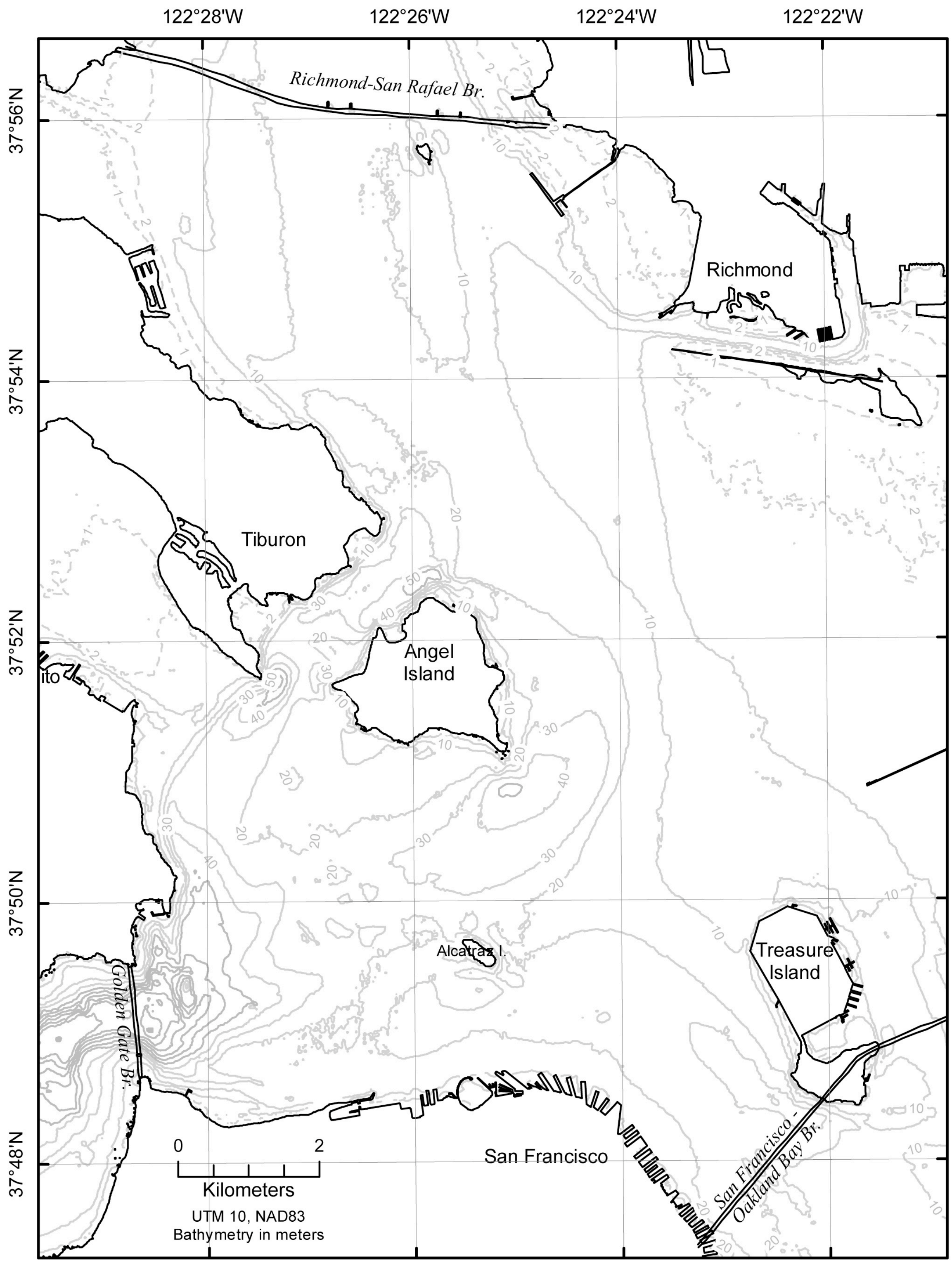

Figure 1-3. Bathymetry map of central San Francisco Bay, California.

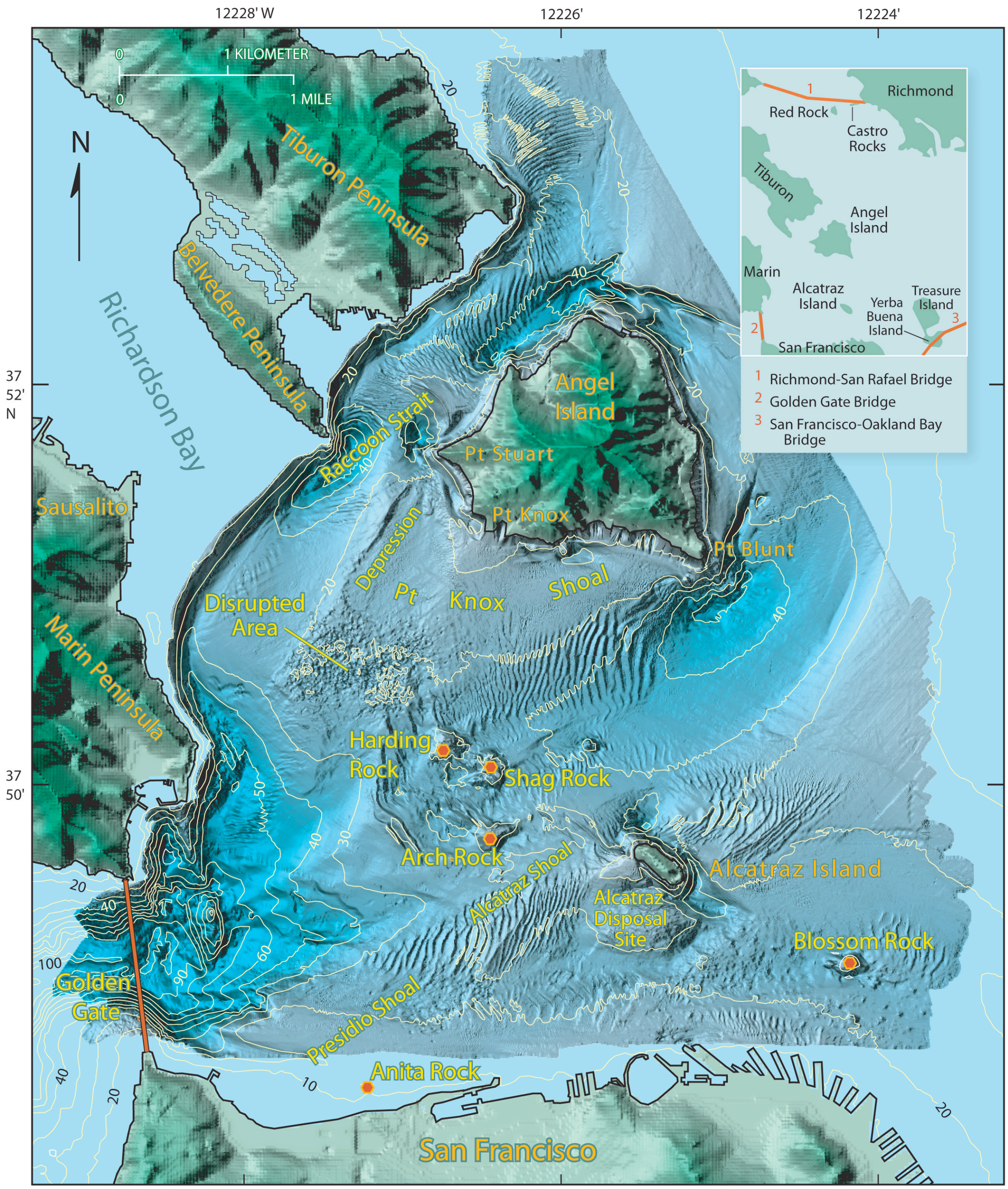

Figure 1-4. Shaded-relief image and bathymetry map of west-central San Francisco Bay, California, based on 1997 multibeam bathymetry. Orange dots mark locations of underwater bedrock knobs. Modified from Chin and others (2004).

Figure 1-5. Shaded-relief image of west-central San Francisco Bay, California, showing active sand-mining lease areas. Orange dots mark locations of underwater bedrock knobs. Modified from Chin and others (2004).

Chapter II. Gravity Cores, Radiocarbon Dates, and Grain-size of Surficial Sediments, Central San Francisco Bay, California

By Donald L. Woodrow, John L. Chin, Florence Wong, Theresa Fregoso, and Bruce Jaffe

Data Set

In 1990 and 1991, the U.S. Geological Survey (USGS) obtained 300+ gravity cores at locations throughout the San Francisco Bay estuary (Anima and others, 2005; U.S. Geological Survey, J-2-90-SF, J-2-91-SF). Seventeen of these cores, referred to hereafter as the A/C cores, were collected in the central San Francisco Bay, east of a line extending from Richardson Bay to Alcatraz Island (Figure 2-1). Four of the A/C cores are reported here (Figure 2-4; Appendix 2-A). The remaining 13 A/C cores will be described in a report that is in preparation.

When originally collected, most of the A/C cores were 2 m long. Because these cores were to be analyzed in the Coastal and Marine Geology (CMG) core lab at the Menlo Park, Calif., USGS campus where the core-splitter accommodates cores as much as 1.5 m long, it was necessary to cut longer cores into two core-segments, an upper segment marked "A" and a lower segment marked "B." This yielded 27 core segments. Cutting, capping and sealing of the A/C cores and core segments in their original core tubes were accomplished on-board ship.

Since their collection in 1990 and 1991, 3 of the A/C cores were lost (90-125B, 90-130B, 90-136B) during the several relocations of the USGS core-storage facility. X-radiographs are not available for those cores (Table 2-1.) Additional losses from the A/C set are 3 box-cores and 6 push-cores collected in Richardson Bay.

Sediments in A/C cores are oxidized and somewhat desiccated. Oxidation of the sediments is demonstrated by their grayish-brown color. Estuarine sediments such as these usually exhibit dark gray or gray-green colors like those seen in Chesapeake Bay (Baucom and others, 2000). Instead, grayish-brown colors typify the sediments in the A/C cores with darker colors seen only as isolated, wispy areas. Core desiccation is evidenced by gaps and open fractures, many of which are encrusted with red crystals of what appear to be iron oxide. The length of any particular core matches the length of that core as seen in its x-radiograph. Thus, desiccation is reflected in the gaps and open fractures, not in core shortening.

Visual Logging Procedures

In preparation for visual logging, walls of the core-tubes were cut lengthwise using the core-splitter available in the CMG lab at Menlo Park. With the cuts in the walls of the core tubes as a guide, a tensioned piano-wire was pulled the length of the core splitting it into two equal parts. Orzech and others (2001) provide details of the core-splitting procedure. One split was wrapped in Saran Wrap, sealed in a D-tube, and returned to the cold room as the archive sample. The other split served as the working sample. After the working sample was described and samples were collected from it, it was shelved in the cold room with the archive sample.

Several cores previously were split and sampled. As an example, core segments 90-124A and 90-124B were split and sampled at 12 positions along the core length. Each sample is approximately 1.5 x 4 cm, with the longest dimensions perpendicular to the core-tube wall.

Other cores yielded fewer samples but the sampling in cores 90-130A and 90-131 disrupted the working split sufficiently that the archive segment was logged instead.

Cores were described in the CMG core lab under an incandescent light, with occasional use of a 10x hand lens. Sediment characteristics noted in the log are lithology, stratification type, strata thickness, sedimentary structures, body fossils, and trace fossils (Appendix 2-A). Sediment color was determined by comparison with a rock-color chart. A grain-size comparator was used to determine grain-size in those few parts of a core judged to have a significant amount of sand-size or coarser material. Weak HCl was dropped along the length of the core to detect effervescence of carbonate-rich sediment or the odor coming from reactions with sulfide minerals. A few cores yielded carbonate effervescence in shelly layers, but only core 90-136 gave a sulfide reaction.

Digital photographs were taken of all cores. Most display monotonous, fine-grained sediment lacking in detail. For that reason, core photos were not included in the core's graphic log (Appendix 2-A), but photographs of the four most diverse cores are displayed in Figure 2-4. All log data were entered into the USGS/CMG FileMaker Pro database (USGS/CMG, Menlo Park).

A few years after the A/C cores were collected, a sophisticated core-logging procedure was made available in the USGS core-analysis facility at Menlo Park. Analysis of whole or half-cores can be carried out using a Multi-Sensor Core Logger (MSCL; GEOTEK LIMITED, Daventry, England) (Orzech and others, 2001). The MSCL determines various geophysical properties of the cored sediments, and it provides digital core photographs. A/C cores were not subjected to MSCL analysis given their desiccation and apparent chemical changes. Photographs of a few core segments were obtained with the digital camera attached to the MSCL, but they were without detail and are not presented here.

X-Radiographs

Full-scale x-radiographs were created for 17 of the 27 A/C core-segments using a portable veterinary x-ray device (Table 2-1.) Data from x-radiographs supplement the lithologic logs with important details about strata thickness, contacts between strata, erosion surfaces, sedimentary structures, trace fossils (especially the presence of burrows thought to have been made by *Sabaco elongatus*), shell materials, bioturbation, and soft-sediment deformation.

Experience gained from visually logging cores and supplementing the logging data with data from x-radiographs provides a strong basis for interpreting the lithology of the two A/C cores available only through x-radiographs.

Sand in West-Central San Francisco Bay

Most of central San Francisco is floored by clayey silts or silty sand but the west-central part of San Francisco Bay is floored by sand, some of it coarse. Much is known about that sand mass via geophysical studies and grain-size analyses of grab-samples. Multibeam bathymetry and sidescan surveys by Chin and others (1998, 2004) illustrate the geometry and distribution of meter-scale bedforms developed on the sand mass and the "dimpled" sediment interface resulting from sand-mining southwest of Angel Island (Figure 2-2). The sand mass is as much as 100 m thick, as determined through acoustic studies (Carlson and McCulloch, 1970; Chin and others, 2004). Grain-size and petrographic data for the sands were obtained by Rubin and McCulloch

(1979) and Greene and Bizzarro (2003). Watt (2003), working with surface samples collected by Chin and others (1998), provides additional grain-size and petrographic data.

The sand mass extends beneath the Golden Gate Bridge then seaward to include the ebb-tidal delta immediately west of the Golden Gate. Barnard and others (2007) have described the geometry and thickness of this sand mass as well as the bedforms found on it. Sand waves of varying dimensions including some believed to be the largest such documented anywhere in the world, are found on these sea floor sands. Barnard and others (2006), Dartnell and others (2006) and Cacchione and others (2003) provide maps and graphic illustrations of the bedforms. Barnard and others (2007) also offer information on the grain-size of the surficial sediments both in the ebb-tide delta.

Although most of the sand in central San Francisco Bay is located west of Angel Island, smaller bodies of sand are found (1) on the floor of Raccoon Strait north of Angel Island, north of the Strait along the Tiburon shore, (2) south of Angel Island, with extensions east and southeast of Alcatraz Island, and (3) extending south from the Richmond-San Rafael Bridge.

As with the sands west of the Golden Gate, prominent bedforms are developed on sands within the bay (Rubin and McCulloch, 1979; Chin and others, 2004). Watt's analyses (2003) of the central bay sediments confirm that the bedforms are made up of sand much like the sand described by Barnard and others (2007) in the channel below and west of the Golden Gate Bridge.

Central San Francisco Bay sand masses have been a target of sand miners for decades with annual output in recent years permitted at 1.5 million tons (Shannin, 2007). Areas included in sand-mining leases are shown in Figure 2-3. Present-day sand mining is concentrated west and southwest of Angel Island, with less frequently mined sites north of Angel Island in Raccoon Strait and south of Angel Island toward Alcatraz Island. In mined areas, the bay floor is pitted and grooved (Chin and others, 2004).

Main Features of the Sediments

Drab, silty clays are now, and have been for the time spanned by these cores, the dominant sediment type over most of the central San Francisco Bay between Angel Island and the eastern shoreline in Richmond, Albany, and Berkeley. Sand makes up less than 10 percent of cores from that area with the exception of core 90-141, which returned 42 cm of fine sand from an easterly extension of the central bay sand mass (Figure 2-4). Radiocarbon dates (see below) indicate that all of the cored sediments are of Holocene age.

Sediment color

Originally, the color of the cored sediments was likely dark gray with a few centimeters of lighter-colored sediment at the top of each core. This is the pattern of color-change with depth generally met with in estuaries like Chesapeake Bay (Baucom and others, 2000) and Long Island Sound, New York (Germano and Associates, 2006). Lyle (1983) refers to the light-to-dark color transition in marine sediments as "…a marker of the Fe(III) – Fe(II) redox boundary." Surficial sediments from South San Francisco Bay illustrate the same color situation where a few centimeters of light-colored, oxidized sediment are found at the sediment/water interface with dark gray (N2-N4) or dark olive-green or greenish gray (5GY or 10GY) sediment below.

However, unlike the modern bay sediment, sediment preserved in the A/C cores from all San Francisco Bay locations uniformly is grayish brown or dark olive gray (2.5Y, 5Y). Brown or olive sediment color apparently was acquired during storage through oxidation, as described by Lyle (1983). What is taken to be the original dark gray color is preserved only as isolated patches or wisps in the centers of a few cores.

Carbonate and Sulfide

Testing with HCl yielded effervescence only in shelly zones and sulfide odors were encountered only in core 90-136A. Thus, carbonate-rich sediments are rare in central San Francisco Bay sediments. Sulfide-rich sediments may have been sampled by these cores but oxidation of the sediments after they were cored looks to have erased any sulfide record.

Stratification

Weakly defined laminae, 1-3 mm thick, with contacts top and bottom grading over 0.25-0.5 millimeters, are common in nearly all of the silty clays. Where bioturbation has been most effective, as in Richardson Bay, strata are poorly defined or strongly disturbed and cut by burrows. Examples of horizontal laminae of very fine sand or coarse silt are seen in cores 90-128, 90-136, 90-140. The laminae are defined clearly with sharp contacts, top and bottom.

Cross-lamination

Sediment movement evidenced by cross-laminae made up of very fine sand, silt, or silty clay exists in seven cores: 90-127, -131, -132, -134, - 137, -139, and -140. Cross-sections of ripples are seen in cores 90-130, -132, -137, and -139. No clear examples were seen of current reversals demonstrated by opposed cross-strata.

Erosion - Sediment erosion or nondeposition is demonstrated by erosion surfaces found in nearly all of the cores. Most erosion surfaces show silty clays immediately above and below with a slight change of gray-shade in the x-radiographs. Such erosion surfaces are obvious in x-radiographs but are nearly impossible to detect visually. More obvious erosion surfaces have sand or sandy silt covering silty clays as in cores 90-125, -133, -134, -139, or shelly sediments covering silty clays as in core 90-136. Cut-and-fill structures are seen in cores 90-134, -136, -137, -138, and -139 where small ripples are developed.

Faults

One core (90-127B, approximately 60 cm below the top of the core), displays what appear to be centimeter-scale, normal faults cutting laminated clayey silts. Micro-scarps with 3-8 mm of vertical offset are draped by laminated clayey silts. The top of the faulted strata is an erosion surface but the micro-scarps generated by the faulting appear not to have been eroded.

Inclined strata

Cores 90-126, -127, and -131 display steeply inclined strata involving all of the cored sediment. It is unclear whether these strata formed (1) as cross-strata in large bedforms, (2) as accretion bedding on channel walls, or (3) as part of a slump block.

Pebbles

Pebble-sized clasts are found in two cores. Core 90-130 carries two, sub-round, pebbles of sandstone, both covered by barnacle spats. Core 90-134 carries a cinder. The fact that one of the clasts is a cinder and all of the clasts are isolated examples suggests that they were dropped into place and are not part of a mass of coarse-grained sediment. Most likely, the cinder was dropped from a steamer passing through Richardson Bay.

Grain Size

Sand, although a rare commodity in the A/C cores, merits further discussion. As noted above, sand is not evenly distributed in central San Francisco Bay. Instead, it is found in three separate masses (Figure 2-5). The major sand mass extends from the Golden Gate Bridge to near Angel Island. It is heavily mined, covered by large bedforms and is made up of coarse sand. A second sand mass floors Raccoon Strait between Angel Island the Tiburon Peninsula and north from there along the Tiburon shore for a few kilometers. Less is known about the Raccoon Strait sand mass but it is finer and has a more limited distribution. A third sand mass extends south from the Richmond-San Rafael Bridge for a few kilometers where it grades into sandy- or silty-clays.

Distribution of the sand indicates two potential sources. The grain-size distribution reported here (Figure 2-5), as well as multibeam bathymetry and backscatter records and sidescan imagery (Greene and Bizarro, 2003), suggest that the large sand mass located west of Angel Island is derived either from outside the bay or from the shoreline rocks and sediments near and beyond the Golden Gate Bridge. A smaller, secondary source of finer-grained sand apparently exists in San Pablo Bay. Sand distribution and the direction of grain-size fining indicates that sand is moved from San Pablo Bay past the Richmond-San Rafael Bridge, then south into the central bay. No evidence exists for mixing of sand from the western sand mass with sand from the northern sand mass. Instead, fine- to medium-grain sands from San Pablo Bay are apparently moved past the Richmond-San Rafael Bridge into central San Francisco Bay and there mixed with silty muds.

Sand in central San Francisco Bay shows a range of sorting with less well-sorted sands east of Angel Island and south of the Richmond-San Rafael Bridge. Sandy- and silty-clays are poorly sorted. The sand grains are subrounded.

It is not known whether either of the two sand sources described above is active presently or if the sand masses are made up of reworked, older, relict sediments. The sand mass west of Angel Island is swept by strong tides. The major bedforms developed on them are likely the result of those tidal currents (Rubin and McCulloch, 1979).

Shelly Sediments

Native peoples found sufficient shellfish available on the floor of central San Francisco Bay to support exploitation on a large scale. Waste shell material accumulated in 425 shell mounds at locations around San Francisco Bay (Luby, Drescher, and Lightfoot, 2006; Nelson, 1909). Many of those shell mounds were developed around central bay. Nearly all of the shell mounds have been obliterated by shoreline development. Today, large concentrations of shells are not found on the floor of central bay. Instead, shelly, clayey silts are found only in and near the mouth of Richardson Bay and at three coring locations in the shallows offshore from Richmond and Berkeley (Figure 2-1).

Isolated shell fragments or whole shells are found in eleven of the A/C cores (90-125, -129, -130, -131, -132, -133, -134, -136, -137, -139, and -140). Articulated shells or single, large, complete, disarticulated shells are found in cores 90-129, -137, -139, and -140. Whole shells identified by Francis Parchaso (written commun., USGS, Menlo Park, Calif.) include the mollusks *Tellina idae* and *Macoma acolasta*. A thin coquina resting on an erosion surface is seen in core 90-136.

A cluster of unusual, small shells was found on the surface of the two greywacke pebbles in core 90-130 and was identified by Parchaso as barnacle attachment plates (spats) made by the barnacle *Balanus* sp. For the shell material to cover most of the pebble surfaces, those surfaces must have been exposed on the bay floor at the time of barnacle colonization with only part of the pebbles buried. This suggests episodic deposition. Spat growth would require an interval of several days or weeks during which sediments were not deposited over the pebbles. Spat growth was stopped by later sedimentation.

Trace Fossils

Cross-sections of burrows are found in 12 of the A/C core segments and are most obvious in x-radiographs. Rarely, the interior walls of burrows are coated with iron oxide, which renders them easily observable in the cut sections. Three types of trace fossil were recognized. The most prominent type is made up of straight or slightly curved, walled burrows 3-30 cm long, taken to be those made by the polychaete *Sabaco elongatus*. A second trace fossil is represented by curved to convolute, short, walled-burrows a few centimeters long. The third variety is seen only in end-on cross-sections. The cross-sections suggest that the burrower moved horizontally. Were it not for the fact that this variety of burrow is always surrounded by a rim of white or red-stained sediment, it might be thought of as a horizontal segment one of the other burrow types. However, none of the other burrows is surrounded by a white rim of sediment.

The three trace fossils identified are not likely to account for all of the bioturbation. Many of the shell-producing mollusks whose shells are found in the cores must have disturbed the sediment/water interface by their movements. In addition, the prolific and diverse benthic fauna in San Francisco Bay (Schaeffer and others, 2007; Nichols and Thompson, 1985) included many other sediment-feeding or burrowing organisms which have left no record other than bioturbated sediments.

Radiocarbon Dates

Nineteen radiocarbon dates from various sources (Table 2-2) were used in this study to determine sedimentation rates both in the older sediments penetrated by the cores and in the youngest sediments seen at or near the sediment/water interface. Eleven of the dates were obtained as part of the present study. In addition, eight dates from cores in and near Richardson Bay have been published (van Geen and others, 1992, 1999).

All of the radiocarbon dates are based either on articulated, whole shells interpreted to be in life-positions or whole, disarticulated shells which showed no sign of abrasion or breakage. Their characteristics suggest that the shells have not been moved from their original locations in the sediment and that their age closely approximates the age of that sediment. For radiocarbon dates based on shell material to reflect accurately the age of the sediment enclosing the shells, and thereby be useful in calculating sedimentation rates, the animals responsible for the shells must be alive at the time of sediment deposition, or the shells must not have undergone erosion and/or transport after death of the organism.

Selection of the shells to be analyzed required careful comparison of cores with their x-radiographs. Shells were examined for signs of abrasion along their edges, and loss of rib detail.

Selected shells were removed from the core, washed in distilled water, air-dried, sealed in glass vials, and shipped to National Ocean Sciences AMS facility (NOSAMS), Woods Hole, Mass., for analysis.

To account for old carbon introduced to bay waters from upwelling along the coast, carbon-14 ages were reservoir-corrected according to the procedure outlined by van Geen and others (1999). To facilitate comparison with bathychronologic data referred to below, the reservoir-corrected ages were converted to calendar years (Stuiver and Pearson, 1993; Stuiver and Becker, 1999; Table 2-2).

Fregoso and Jaffe (written commun., 2009) provided synthetic cores for the five central San Francisco Bay locations at which carbon-14 dates are available (core locations 90-129, -131, -132, -137, and -139). Synthetic cores were compiled following the procedures described by Higgins and others (2005, 2007). Jaffe and his colleagues (Fregoso and others, 2008) have tested this approach as a guide to sedimentation history during the past 150+ years, the time interval for which bathymetric surveys are available for San Francisco Bay. They plotted the temporally significant records of cesium-13 and other geochemical markers against the dates associated with the synthetic cores at many locations in San Francisco Bay (Higgins and others, 2007; Jaffe, Smith, and Torresan, 1998; Jaffe, Smith, and Foxgrover, 2007). The synthetic-core dates and the dates associated with the geochemical data are in close agreement.

By way of contrast, dates associated with five synthetic cores when compared with calendar dates converted from reservoir-corrected carbon-14 dates as illustrated in Appendix 2-A, demonstrate that the two arrays of calendar-corrected radiocarbon dates do not agree. The calendar dates either are older than the date of the bathymetry survey at the same depth in the synthetic core, or come from depths in the sediment greater than the length of the synthetic core. A further complication is apparent in cores 90-131 and -139 where two older radiocarbon dates come from sediment *above* a younger radiocarbon date. Thus, some of the calendar-corrected, radiocarbon dates are inconsistent with dates from synthetic cores or they are inconsistent with other radiocarbon dates. All this suggests erosion and rearrangement of the shells which served as the source of the carbon-14 ages cited here. On the other hand, radiocarbon or other radiometric-dating techniques provide the only sediment ages available in the absence of bathychronologic data.

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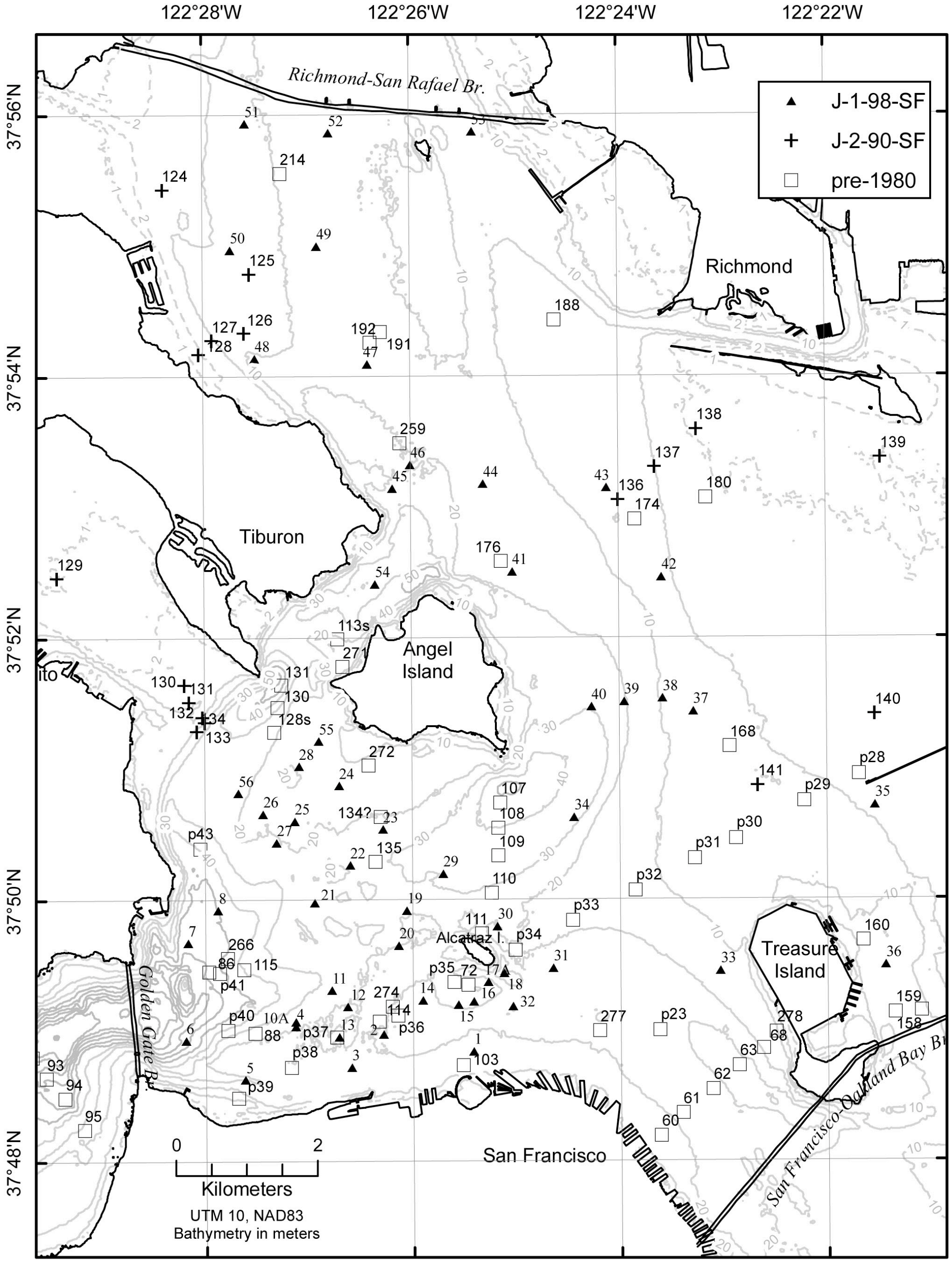


Figure 2-1. Location map, central San Francisco Bay, California. Anima/Clifton (U.S. Geological Survey, J-2-90-SF) gravity cores: +. Grain-size samples: open boxes (pre-1980 samples from Rubin and McCulloch, 1979) and solid triangles (U.S. Geological Survey, J-1-98-SF; Watt, 2003).

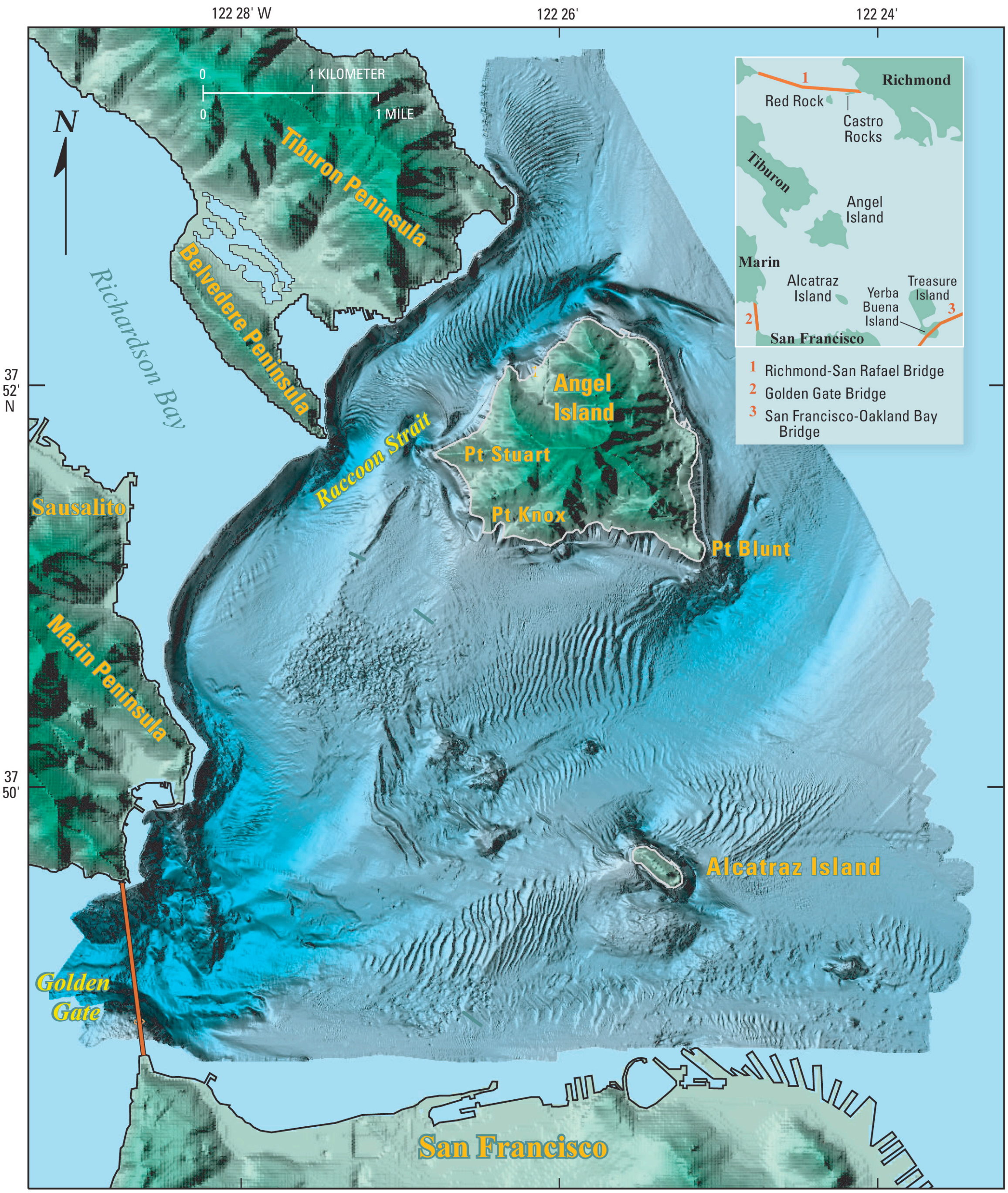


Figure 2-2. Bottom configuration of central San Francisco Bay, California. Deeper waters shown in blue. Prominent bedforms and pocked (mined) areas in shallower water around Angel and Alcatraz Islands. Dredge-spoil mound south of Alcatraz Island. Modified from Chin and others (2004).

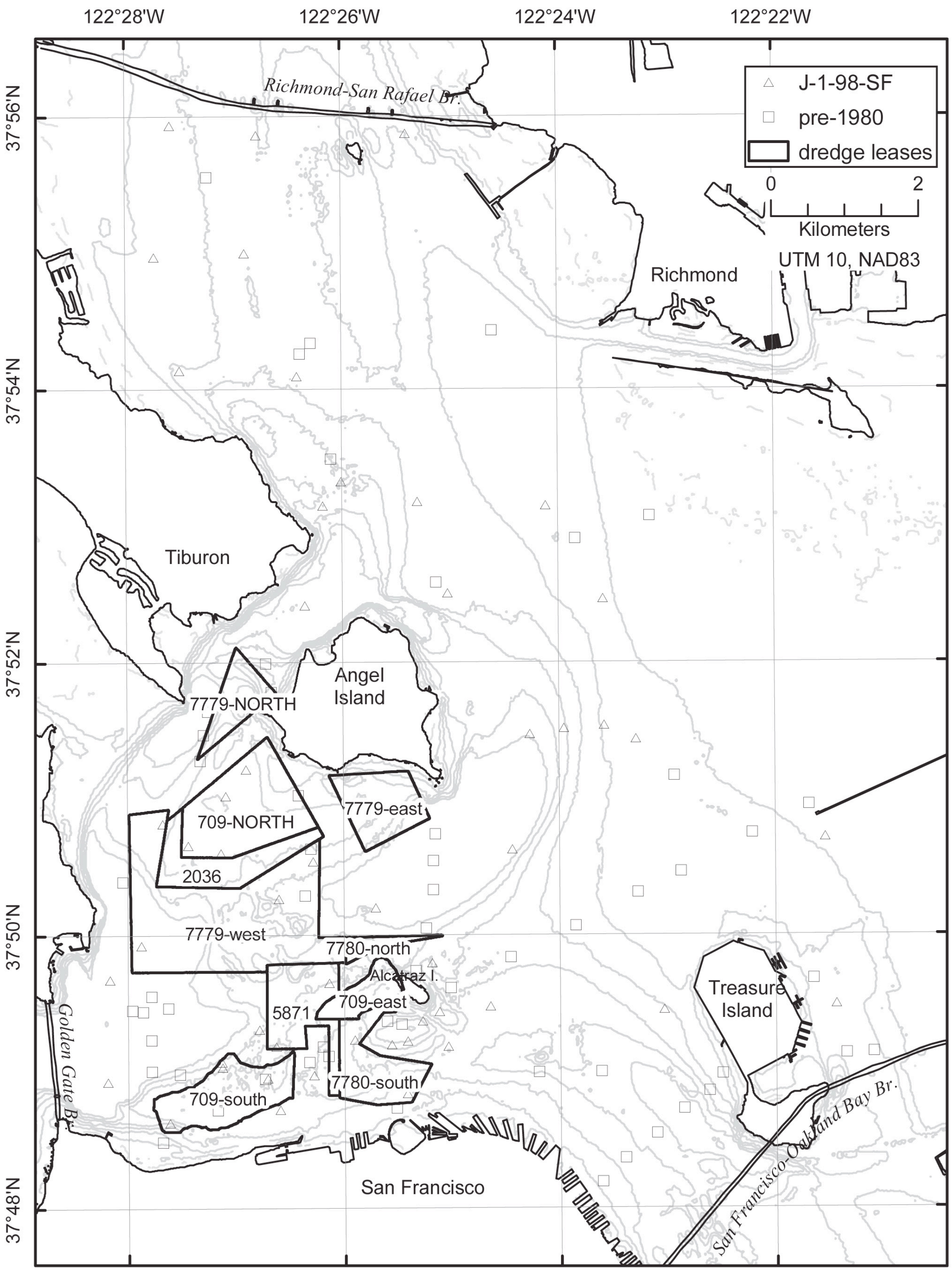


Figure 2-3. Areas leased for sand-mining in San Francisco Bay, California.

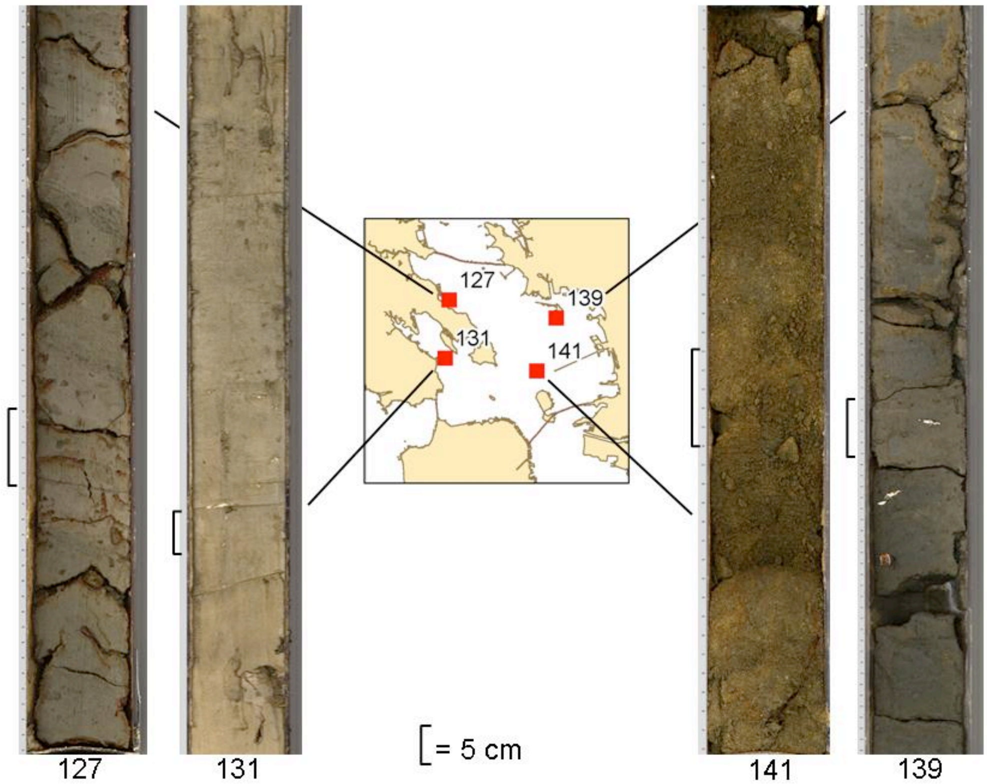


Figure 2-4. Anima/Clifton gravity cores from central San Francisco Bay, California (U.S. Geological Survey, J-2-90-SF). 127 - Inclined strata. Many Anima/Clifton cores fractured due to desiccation. 131 - Oxidized silty muds typical of strata over much of central San Francisco Bay. 90 - Dark, silty muds offshore of Richmond Harbor. 141 - Sand. Core logs in Appendix 2-A.

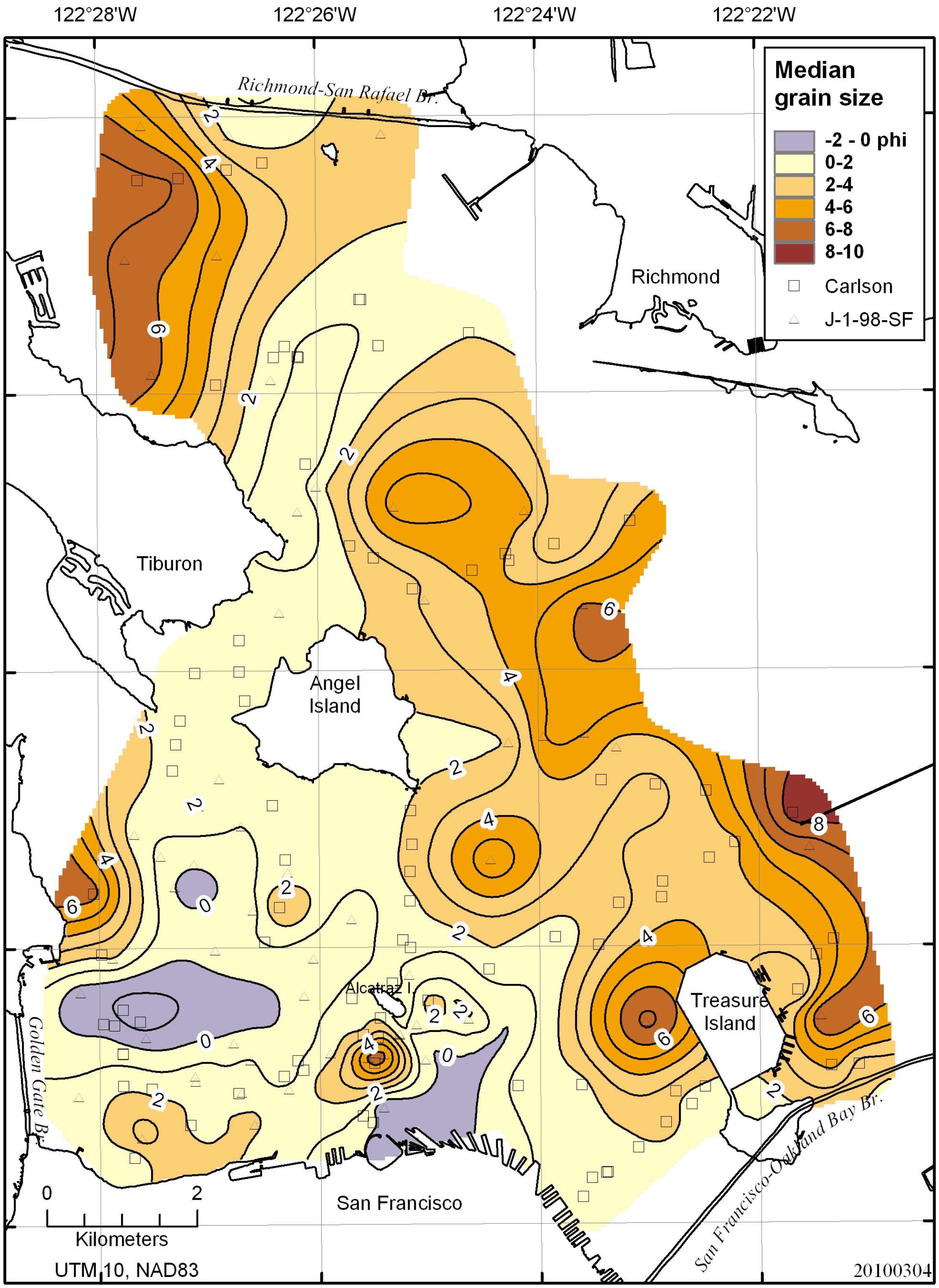


Figure 2-5. Grain-size distribution based on median grain-size values, central San Francisco Bay, California (Appendix 2-B; Watt, 2003; Rubin and McCulloch, 1979).

Table 2-1. Availability of Anima/Clifton core segments and x-radiographs, central San Francisco Bay, California

Core number	Core available	X-radiograph available
90-124A	Y	Y
90-124B	Y	Y
90-125*	Y	N
90-126	Y	Y
90-127A	Y	Y
90-127B	Y	Y
90-128A	Y	Y
90-128B	Y	Y
90-129A	Y	N
90-129B	Y	N
90-130A*	Y	Y
90-131A	Y	Y
90-131B	Y	N
90-132A	Y	N
90-132B	Y	Y
90-133	Y	Y
90-134A	Y	Y
90-134B	Y	Y
90-0136A	Y	Y
90-137	Y	Y
90-138A	Y	N
90-138B	Y	N
90-139A	Y	Y
90-139B	Y	Y
90-140A	Y	Y
90-140B	N	Y
90-141	Y	Y

Table 2-2. Radiocarbon dates, central San Francisco Bay					
Core number	Depth in core (cm)	Core location	^{14}C age in years	^{14}C age with reservoir correction in years	Calendar Age - AD
a. Dates from Anima/Clifton cores (This study)					
90-129A	99	Richardson Bay	1,030±20	(1)765	1510
90_129A	142	Richardson Bay	2,220±20	(1)1,985	1420
90-130A	45-50	Richardson Bay	715±30	(1)480	1880
90-131B	14-15	Richardson Bay	1,110±20	(1)865	1460
90-131B	69-70	Richardson Bay	930±25	(1)695	1656
90-131B	72-73	Richardson Bay	1,220±35	(1)985	1406
90-132A	46	Richardson Bay	565±25	(1)330	329
90-132A	73	Richardson Bay	705±30	(1)470	1891
90-137	83-84	Richmond	750±25	(2)1,590	1858
90-139A	112-113	Richmond	2,190±30	(2)150	810
90-139A	113.5-115.5	Richmond	2,530±30	(2)1,930	480
b. Dates from cores taken at the mouth of Richardson Bay (van Geen and others, 1992)					
(Core not numbered)	105	Richardson Bay	760±70	(1)525	1410
	220	Richardson Bay	1,190±70	(1)955	1041
	520	Richardson Bay	2,690±60	(1)2,455	530
	820	Richardson Bay	3,720±70	(1)3485	1750
	1,090	Richardson Bay	4,390±80	(1)4,155	2460
c. Dates from cores taken at the mouth of Richardson Bay (van Geen and others, 1999)					
RB923	107	Richardson Bay	1,250±60	(1)1,015	1020
RB92-3	140	Richardson Bay	1,700±50	(1)1,465	610
Near RB92-3	340-400	Richardson Bay	3,460±130	(1)3,225	1475

(1)reservoir correction: 235 yrs.; (2)reservoir correction: 600 yrs. (van Geen and others, 1999)

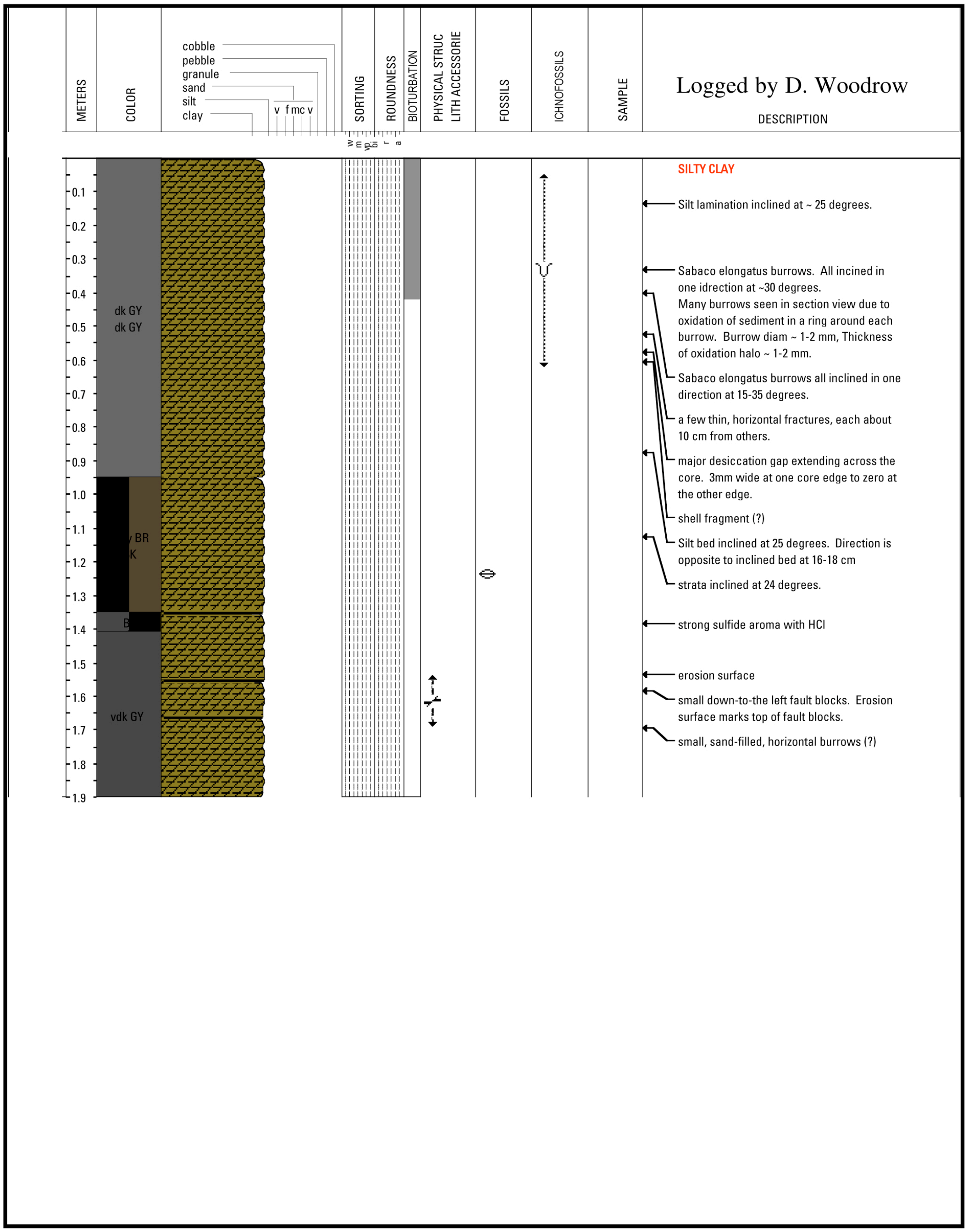
Appendix 2-A - Graphic Logs of Selected Cores From Central San Francisco Bay

U.S. GEOLOGICAL SURVEY

Central San Francisco Bay

Collected: 2/8/1990
Water Depth: 18 feet

Cruise: J-2-90-SF
Site: 90-127
lat 37° 54' 10.1" N., long 122° 27' 32.8" W. (WGS84 datum)

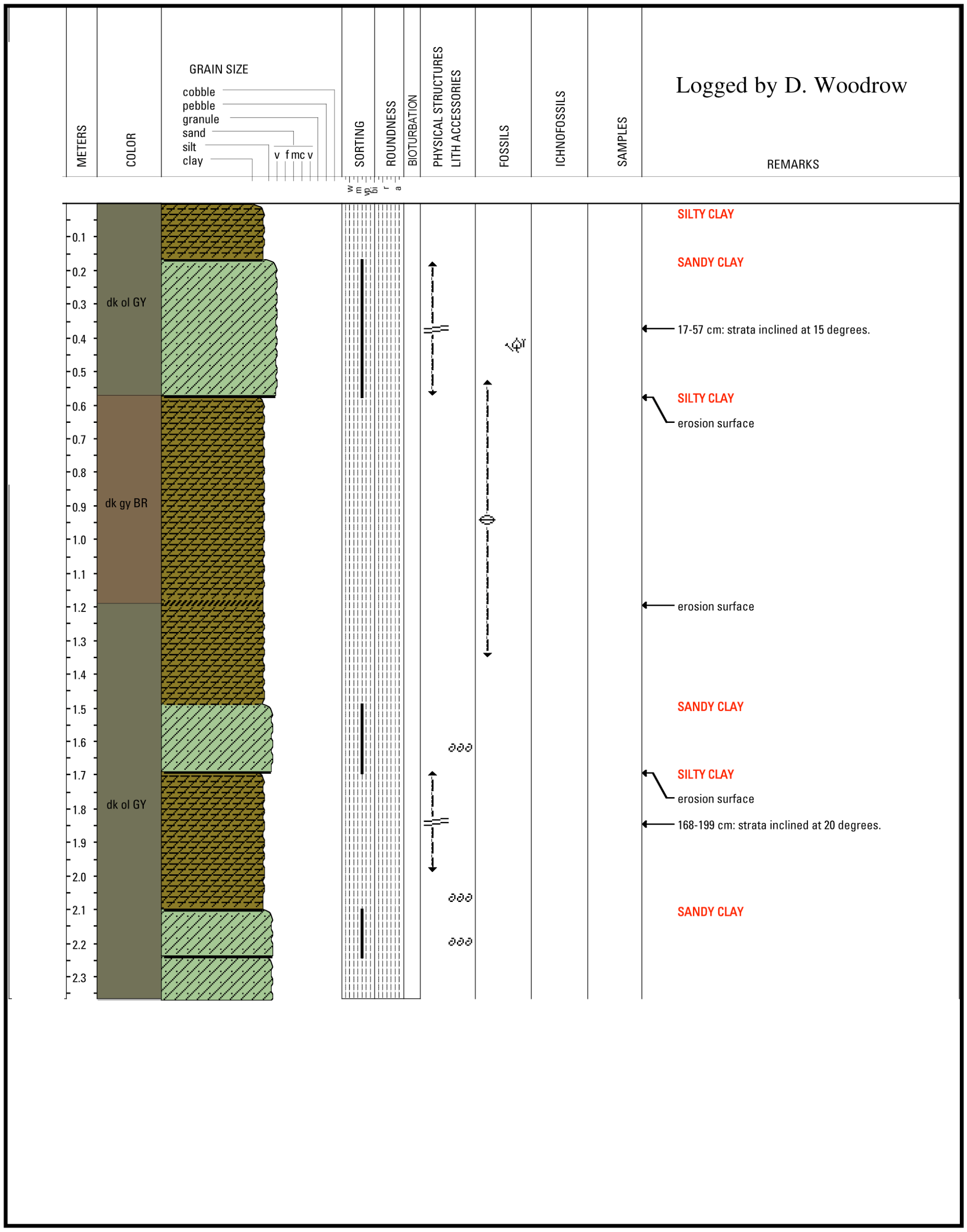


U.S. GEOLOGICAL SURVEY

Central San Francisco Bay

Collected: 2/9/1990
Water Depth: 20 feet

Cruise: J-2-90-SF
Site: 90-131 lat 37° 51' 18.4" N., long 122° 28' 5.4" W. (WGS84 datum)



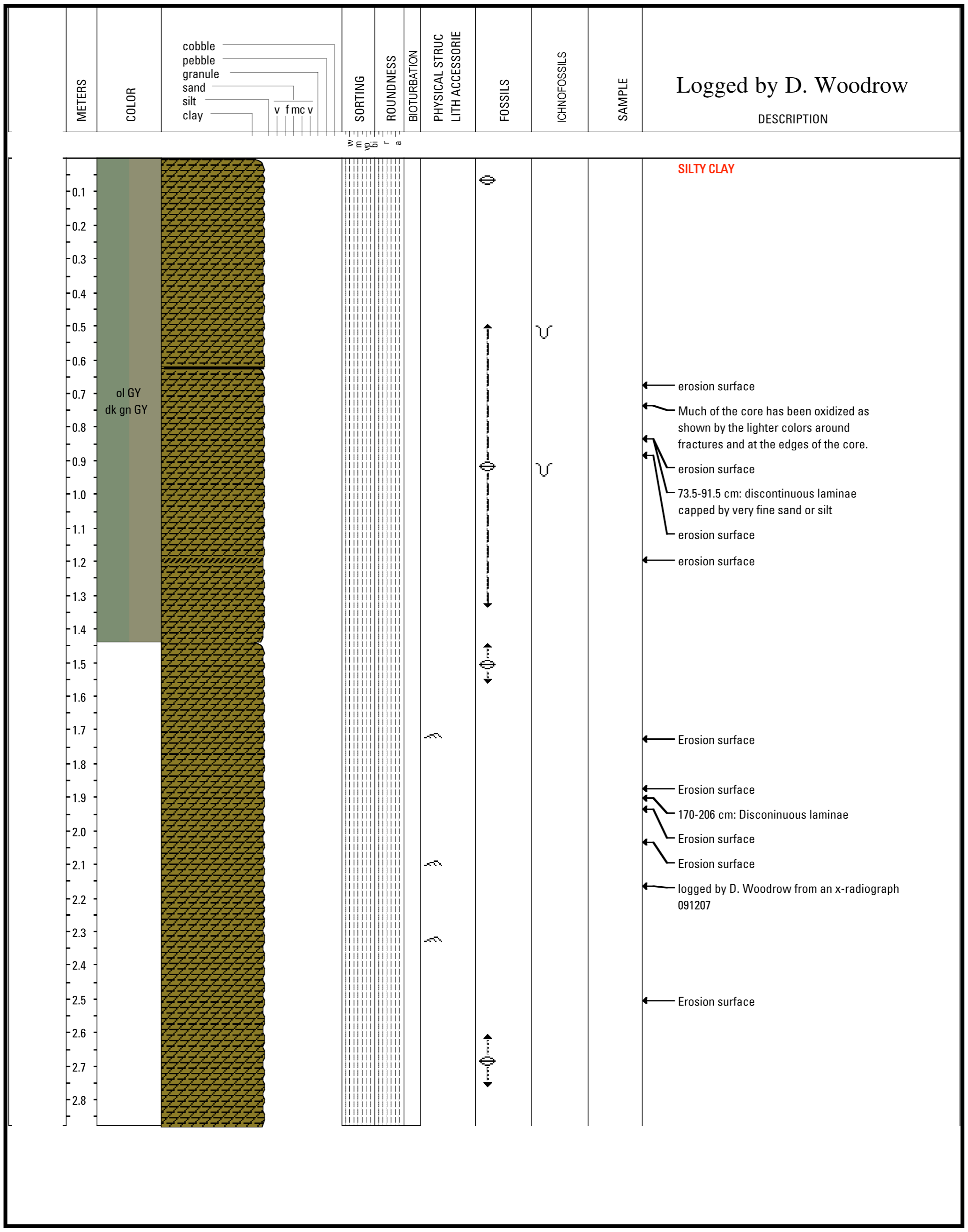
U.S. GEOLOGICAL SURVEY

Central San Francisco Bay

Collected: 2/9/1990
Water Depth: 2 meters

Cruise: J-2-90-SF

Site: 90-139 lat 37° 53' 13.3" N., long 122° 21' 16.9" W. (WGS84 datum)

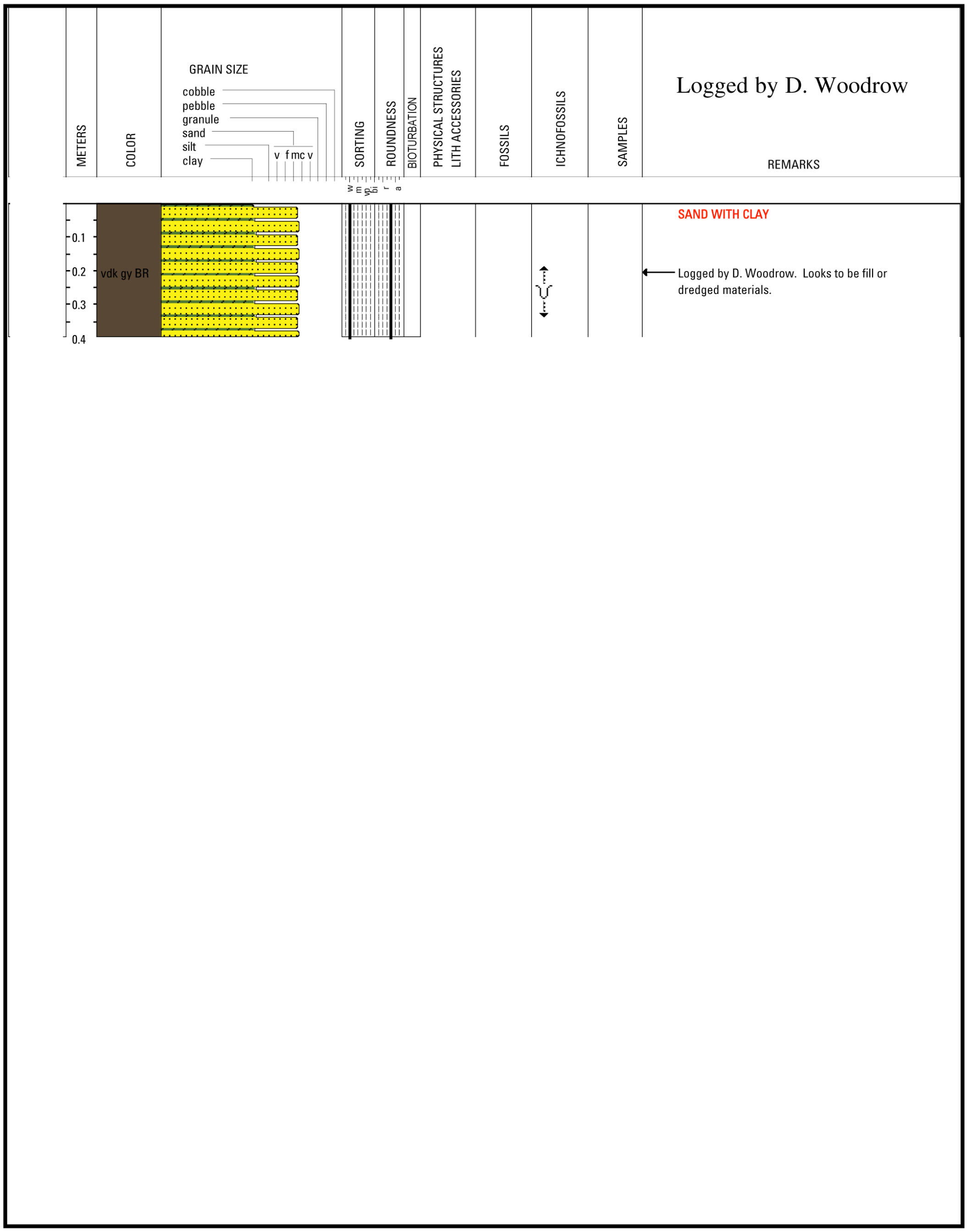


U.S. GEOLOGICAL SURVEY

Collected: 2/9/1990
Water Depth: 31 feet

Cruise: J-2-90-SF
Site: 90-141

lat 37° 50' 31.3" N., long 122° 22' 24.1" W. (WGS84 datum)



Appendix 2-B. Table of Samples Used in Calculation of Grain-Size Distribution for West-Central San Francisco Bay

Appendix 2-B is presented as a set of spreadsheet files in
http://pubs.usgs.gov/of/2010/1130/of2010-1130_appendix2-b_grainsize
in several file formats.

Chapter III. 1998 Central San Francisco Bay Foraminiferal Study

By Mary McGann

Abstract

One of the strongest tidal flows in the world travels through the Golden Gate into San Francisco Bay. As a result, sediment is in constant motion as currents exchange water between the marine realm outside the estuary and the three subembayments (central, north, and south bays) within. Although the distribution of foraminifera in most of San Francisco Bay is well documented, that is not the case for central bay. The extremely high-energy conditions present in this region create a challenging environment in which benthic foraminifera must reproduce and establish their populations. As a result, depauperate foraminiferal faunas as low as 0.1 specimens/g dry sediment are common.

Fifty-five grab samples obtained in 1998 were analyzed to characterize the foraminiferal fauna of central bay. Thirty-five species were identified, including the invasive Japanese species *Trochammina hadai* which was introduced into the estuary in the early 1980s. A cluster analysis grouped the samples into four clusters. The Shallow Eastern Bay Assemblage is characterized by a marsh to shallow-subtidal arenaceous fauna, dominated by *Trochammina hadai* but also including *Trochammina inflata, Trochammina macrescens, Haplophragmoides subinvolutum*, and *Miliammina fusca*. In contrast, the Intermediate Eastern Bay, Deep Western Bay Estuarine, and Deep Western Bay Marine Assemblages are dominated by calcareous taxa, most notably *Ammonia beccarii, Elphidium excavatum*, and *Elphidiella hannai*. *Ammonia beccarii* is most abundant in the warmer, intermediate depths of eastern central bay, abundances of *Elphidium excavatum* peak in the cooler estuarine water near Alcatraz Island, and *Elphidiella hannai* thrives in the cold water west of Angel Island in a transitional setting between the deep subtidal estuarine and the nearshore marine environments. The presence of marine-indicating species as far east as Angel Island suggests that western central bay is the most oceanically-influenced region of the estuary.

Evidence of sediment transport is widespread in the 1998 samples. Thecamoebians were recovered at a third of the sites, most of which are far from their local freshwater sources. Similarly, marsh-indicating foraminifera were found at several deep water sites where they would not normally live. Anthropogenic-sourced welding slag and paint beads were recovered far from docks, radiolarian and planktic foraminifera of marine origin were found as far north as the Richmond-San Rafael Bridge, and bubble-wall shards of volcanic glass were found at nearly half the sites although no volcanic source is in the vicinity.

Introduction

Although the distribution of foraminifera in San Francisco Bay is fairly well documented at about 350 sites by investigations undertaken from the 1960s to the early 1980s (Means, 1965; Slater, 1965; Quinterno, 1968; Locke, 1971; Connor, 1975; Wagner, 1978; Arnal and others, 1980; Sloan, unpublished data from 1980-1981), only 20 of those published were located in central bay. As a result, the character of the foraminiferal assemblages of central bay remain the most poorly described of the entire estuary. In addition, shortly after the completion of these studies, a common estuarine Japanese foraminifera *Trochammina hadai* Uchio was introduced into San Francisco Bay, probably transported from Japan to western North America in ballast sediment, in anchor mud, or in sediments associated with oysters imported for mariculture (McGann and others, 2000). Following the species' arrival between 1981 and 1983, *Trochammina hadai* proliferated in its new environment, becoming one of the dominant foraminifers in the estuary. Therefore, the goal of this present study is to investigate the distribution of both native and introduced foraminifera in central bay at the end of the 20th Century.

Setting

San Francisco Bay is the largest estuary on the west coast of the United States (Conomos and others, 1985), created from a structural trough that formed during the late Cenozoic (Lawson, 1894, 1914; Atwater and others, 1977; Atwater, 1979) which was later inundated by seawater during late Pleistocene and Holocene deglaciation (Gilbert, 1917; Louderback, 1941, 1951). San Francisco Bay consists of three subembayments (Figure 3-1): north bay (including San Pablo and Suisun Bays as well as the shallow embayments of Grizzly and Honker Bays), central bay (including Richardson Bay), and south bay (Chin and others, 2004).

Central bay, defined here to encompass the area from Point San Pablo and Point San Pedro to the north, the Golden Gate Bridge to the west, the shores of Richmond and Berkeley to the east, and the San Francisco-Oakland Bay Bridge to the south (Figure 3-2) has the largest water volume of the entire estuary (The Bay Institute, 1998; Chin and others, 2004). Despite this fact, the region averages only 11 m mean lower low water (MLLW; the average height of the lower of the two daily low tides) depth, and submerged rock knobs (Anita, Blossom, Harding, Shag, and Arch Rocks) are present that have been an ongoing concern to the shipping industry (Chin and others, 2004). In contrast, the deepest part of San Francisco Bay is situated in western central bay near the Golden Gate Bridge, reaching a maximum depth of 113 m (Hanes and Barnard, 2007).

One of the strongest tidal flows in the world occurs at the Golden Gate, with currents that exceed 2.5 m/s, an enormous tidal prism of 2×10^9 m^3, and about 500 billion gallons of water moving through the narrow opening each six-hour period (Figure 3-3; San Francisco Chronicle, 2006; Hanes and Barnard, 2007; Barnard and others, 2008). As a result, sediment is constantly in motion, moving in and out of San Francisco Bay, forming large sand waves both in central bay and just seaward of the Golden Gate (Chin and others, 2004; Hanes and Barnard, 2007). At times, sediment-laden currents also flow between central bay and both north and south bays (Figures 3-3A, 3-3C); at other times they flow stronger into one or the other (Figures 3-3B, 3-3C). With each tidal cycle there is also a slack tide when the currents are weak and sediment may be deposited briefly (Figure 3-3E). Because of this dynamic environment, western central bay is deep and characterized by the presence of the coarsest sediment in the estuary as finer sediments are carried away (Rubin and McCulloch, 1979). West central San Francisco Bay is also the most oceanically-influenced region because water is exchanged with the nearby marine realm through the Golden Gate (Long-Term Management Strategy, 1998). In contrast, the eastern portion of central bay is very shallow and brackish in character because it experiences no marine-exchange, being dominated by fine grained sediment that is prone to wind-generated currents instead of strong tidal scouring (Figure 3-3A-E; San Francisco Estuary Institute, 1997; Long-Term Management Strategy, 1998).

Previous Work

Several scientific cruises were undertaken near the turn of the 20th century with the purpose of reporting on the distribution of marine organisms (including foraminifera) in the Pacific Ocean. Among these were the voyages of the H.M.S. *Challenger* from 1873-76 (Brady, 1884), the U.S.S. *Albatross* from 1888-1911 (Flint, 1899; Bagg, 1908; Cushman 1910, 1911, 1913, 1914, 1915, 1917), and the U.S.S. *Nero* from 1899-1900 (Flint, 1905). However, these studies focused on the deeper waters of the Pacific Ocean, leaving the California coast untouched. This is somewhat surprising since San Francisco Bay was the home port of the *Albatross* for many years. However, no collections were made within the bay or on its adjacent coastline in those early years (Hanna and Church, 1927). It was not until 1912-1913, after the *Albatross* was found to be unseaworthy, that she explored San Francisco Bay in detail, acquiring 43 dredge samples from south bay to the Carquinez Strait (Packard, 1918b). Unfortunately, only reports on the sedimentology, overlying oceanographic parameters (Sumner and others, 1914), and the distribution of mollusks (Packard, 1918a, 1918b) were published; no foraminifera were ever studied.

The earliest published study of foraminifera in the vicinity of San Francisco Bay was that of Hanna and Church (1927) who reported on a single sediment sample collected for the Steinhart Aquarium in January 1926 between Point Reyes and the Farallon Islands at a depth of about 137-155 m. Thirty-seven species were described, including several reported for the first time from the region. Shortly thereafter, McDonald and Diediker (1930) published the results of a study of 19 locations in San Francisco Bay from south bay to Suisun Bay, seven of which were in central bay (Figure 3-2), as well as two additional sites outside the Golden Gate (Seal Rock and Half Moon Bay). Unfortunately, they did not state when they acquired their samples. The authors identified eight species of foraminifera within the bay and 13 outside the bay, with living specimens recovered at nearly every station. They concluded that the higher species diversity outside the bay reflected more favorable conditions for the foraminifera, that bottom conditions within the bay did not seem to have an influence on “the life of the forms, ” and that Bulls Head Point (western Suisun Bay near Martinez) roughly defined the limit of the foraminiferal occurrence in San Francisco Bay. McDonald and Diediker (1930) also suggested which environmental factors (salinity and temperature) seemed to correlate with the presence of each of the most abundant species.

It was not until the 1960s to early 1980s that the distribution of foraminifera in San Francisco Bay was investigated in detail. Those works include Slater (1965) in Suisun Bay, Locke (1971) in San Pablo Bay, Means (1965) and Connor (1975) in Richardson Bay, and Quinterno (1968) and Arnal and others (1980) in south bay, as well as Wagner (1978) and Sloan (unpublished data from 1980-1981) in two studies with scattered bay-wide sites. The samples applicable to this present study in central bay are those of Locke (1971) who described foraminifera from nine sites from Point San Pablo to the Richmond-San Rafael Bridge (Figure 3-2); Means’ (1965) report on four sites in Raccoon Strait as well as four from west of Angel Island; and Sloan’s (unpublished data) investigation of foraminifera in August 1980 and February 1981 from a single site on the eastern side of the bay in the shallow waters near the Berkeley Pier. In addition, Wagner (1978) obtained three grab samples between the Tiburon Peninsula and Richmond, and three more in the deep waters between Alcatraz Island and the Golden Gate Bridge, but only provided faunal counts for the latter. All of these investigations occurred before the introduction of *T. hadai*.

Methods

Fieldwork was undertaken in early 1998 by the U.S. Geological Survey (USGS) to document the nature and thickness of Quaternary sediment in central bay. In conjunction with a multibeam survey conducted in 1997 (U.S. Geological Survey, C-1-97-SF and C2-97-SF), new seismic-reflection and sidescan sonar data was collected onboard the *RV David Johnston* (USGS CMG cruise J-1-98-SF) from January 8-23 to investigate the surficial and shallow subsurface deposits of the bay. In addition, 56 samples were obtained by a small Van Veen grab sampler to characterize the texture of surface sediments for sediment-distribution and transport studies (Figure 3-2).

In 2008, a decade after the samples were collected, sediment from all but one of the 56 samples was analyzed for foraminifera (Table 3-1). Sediment from sample 9 was no longer available and is assumed to have been used in its entirety for grain-size analysis. It is unfortunate that these samples were collected years earlier because staining them in order to recognize foraminifera that were living or recently alive at the time of collection (Bernhard, 1988, 2000) was no longer practical. Instead, the sediment samples simply were wet-sieved through nested 63 µm, 150 µm and 1.0 mm screens to remove the clays (<63 µm) and separate the size fractions while minimizing damage to the finer screens. The sediment retained on the screens was transferred to filter paper and air-dried.

The >63 µm to <1.0 mm fraction of all samples was subjected to floatation by sodium polytungstate in order to concentrate the foraminifers before picking. Foraminifers were then extracted from the light fraction. Samples were split with the aid of a microsplitter into an aliquot containing at least 300 benthic foraminifers and all specimens were picked and identified. If the sample contained <300 foraminifers, all that were present were picked. A few representative specimens of the other biologic, sedimentologic, and anthropogenic constituents present in the samples also were picked and mounted on the slides. The slides and residues are on file at the USGS, Menlo Park, California.

Owing to the small number of foraminifers recovered in many of the samples, relative foraminiferal species abundances were computed using a sum of benthic foraminifers in those samples in which at least 50 foraminifers were recovered (40 of 55 samples). Once converted to frequency data, a Q-mode cluster analysis described the relationship between the benthic foraminiferal assemblages of these samples. The cluster analysis grouped the samples according to their degree of similarity. Clustering was based on a square root transformation of the data, a Bray-Curtis similarity coefficient, and was amalgamated by a group-averaged linkage strategy. Primer v. 6, a statistical software package created by Primer-E, Ltd., was used for this analysis (Clarke and Gorley, 2006).

Results

Thirty-five species of arenaceous and calcareous benthic foraminifers were identified in the samples collected in central bay in 1998 (Table 3-2). All are found today in nearshore, shallow embayments, or estuaries along the Pacific Coast of North America (Ingle, 1980; Jennings and Nelson, 1992; McCormick and others, 1994; McGann, 2007; Murray, 1991; Phleger, 1967; Scott and others, 1976). Included among these is the invasive species *Trochammina hadai*, which has now been found in 14 ports and estuaries from San Diego Bay to Prince William Sound (McGann and others, 2000; McGann, unpublished data). Of the species recovered in central bay, the most common are *Ammonia beccarii* (Linné), *Elphidiella hannai*

(Cushman and Grant), *Elphidium excavatum* (Terquem), *Trochammina hadai*, and *Trochammina inflata* (Montagu) (Table 3-3). In the 1998 survey, *T. hadai* was present throughout much of central bay, occurring at 46 of 55 sites. Species diversity ranged from 3-20 species/sample, with a mean of 9 species/sample.

The Q-mode cluster analysis of the 1998 central bay foraminiferal census data grouped the samples into four clusters and two outliers (Figure 3-4). These data are interpreted as representing Shallow Eastern Bay, Intermediate Eastern Bay, Deep Western Bay Estuarine, and Deep Western Bay Marine cluster assemblages as well as Intermediate Eastern Bay and Deep Western Bay Estuarine outliers.

Discussion

Cluster Analysis and Distribution of Foraminifera

Eight samples (35, 37, 38, 43, 44, 49, 50, and 51) located at water depths of 6 to 14 m (averaging 9 m; Table 3-4) in the middle of central bay from the Richmond-San Rafael Bridge to the western end of the Berkeley Pier (Figure 3-5) grouped to form the Shallow Eastern Bay Assemblage. Typically, such shallow sites are stressed environments because of wide ranging water temperatures and salinity as well as high organic input. As a result, marsh to shallow subtidal estuarine environments are often characterized by low species diversity (Murray, 1973; Phleger, 1970) and dominance by arenaceous taxa due to low sediment pH which dissolves calcareous tests, especially when the pH is below 7.0 (Arnal, 1961; Jennings and Nelson, 1992; Parker and Athern, 1959; Phleger, 1967; Scott and Medioli, 1980; Scott and Leckie, 1990). The fauna of this assemblage is as expected, with low species diversity (mean = 6 species/sample), rare calcareous species (accounting for <2 percent of the assemblage on average), and an abundance of arenaceous specimens. *Trochammina hadai* dominates the assemblage (averaging 77 percent), *Trochammina inflata* is common (17 percent), and the marsh-indicating species *Haplophragmoides subinvolutum* Cushman and McCulloch, *Miliammina fusca* (Brady), *Trochammina macrescens* Brady, and questionable *Ammobaculites exiguus* Cushman and Bronnimann are present. Because a similar arenaceous-dominated fauna is present in the marshes of Richmond (Figure 3-2; Weber and Casazza, 2006), it is assumed the Shallow Eastern Bay Assemblage extends to the eastern coastline of central bay. This region is characterized by low average current velocity for the entire tidal cycle (Figure 3-3A-E) and the sediment grain size of the samples reflect this by ranging from fine to coarse silt (averaging 5.59 phi units; medium silt; Watt, 2003) which is the finest among all of the samples in this study.

The cluster analysis strongly separated the samples assigned to the Shallow Eastern Bay Assemblage from all of the other samples (Figure 3-4). Whereas the fauna of this assemblage is dominated by arenaceous taxa, those of all three of the remaining clusters and two outliers are dominated by calcareous specimens.

Like the Shallow Eastern Bay Assemblage, the Intermediate Eastern Bay Assemblage is a grouping of eight samples (15, 16, 17a, 34, 36, 39, 41, and 47). These samples are located along a crescent from the eastern side of the Tiburon Peninsula and Angel Island south to near Fort Mason in San Francisco with one additional sample on the eastern side of Treasure Island (Figure 3-5). The samples range in depth from 13-35 m (averaging 18 m) and are fine silt to coarse sand with shells (Table 3-5), averaging 4.77 phi units (coarse silt; Watt, 2003). Associated with this increase in grain size is an increase in average current velocity in this region, particularly at peak ebb and flood tides (Figure 3-3A, 3-3C). Species diversity increases in this assemblage (11 species/sample), reflecting deepening water and more stable environmental conditions. Although *Trochammina hadai* continues to be a significant constituent of this assemblage (averaging 28 percent), *Ammonia beccarii* is the most abundant species in the assemblage (30 percent) and *Elphidium excavatum* (14 percent) and *Elphidiella hannai* (14 percent) are common. *Ammonia beccarii* lives in shallow, brackish to hypersaline, warm temperate to tropical environments (optimum range of 24-30°C; Bradshaw, 1957) and is not found north of about Samish Bay, Washington (Scott, 1974; Jones and Ross, 1979; Murray, 1991). *Elphidium excavatum* also lives in wide-ranging salinity regimes (11-35 psu), but prefers colder water temperatures than *Ammonia beccarii* (0-12°C; tolerates up to 22°C) (Brodniewicz, 1965; Haake, 1967; Murray, 1965, 1970). Like *Elphidium excavatum*, *Elphidiella hannai* prefers cold water, living in estuaries and on the inner shelf as far north as Alaska (Cockbain, 1963 and Bergen and O'Neil, 1979, as *Elphidiella nitida* Cushman; Echols and Armentrout, 1980; Murray, 1991). Abundant *Ammonia beccarii* in the Intermediate Eastern Bay Assemblage suggests this assemblage prefers warm and somewhat shallow conditions, typical of modern faunas in San Pablo and Richardson Bays and south bay (Arnal and others, 1980; Locke, 1971; McGann and Sloan, 1999; Means, 1965; Quinterno, 1968; Slater, 1965).

Three samples of the Intermediate Eastern Bay Assemblage (15, 16, and 17a) were obtained from the Alcatraz disposal site southwest of Alcatraz Island (Figure 3-5). Although first used in 1894 (Long-Term Management Strategy, 1994), this site was formally designated a disposal site in 1972 (Long-Term Management Strategy, 1998) and continued to be used heavily until 1991 (Chin and others, 2004). The native material at the site is predominately fine to coarse sand with occasional finer silt; nearby are areas of bedrock and boulders (Long-Term Management Strategy, 1998). In contrast, the dredged material dumped in the area is mostly fine-grained material (clays and silts) with elevated levels of most metals, oil, grease, TRPHs and PAHs (Long-Term Management Strategy, 1998). Only sample 17a contains abundant (18.3 percent) *Haynesina germanica* (Ehrenberg) which is a species preferring organic matter (Arnal and others, 1980), even though this sample is more coarse (2.57 phi units; fine sand) than samples 15 and 16 (6.05-6.26 phi units; fine silt; Table 3-5). Interestingly, *Eggerella advena*, another organic matter-favoring species common to waste discharge regions (Bates and Spencer, 1979; Clark, 1971; Schafer and Cole, 1974; Schafer and Young, 1977; Watkins, 1961; McGann and others, 2003) and a pioneer colonizer in former polluted areas (Schafer, 1982), was not present in any of these three samples although it was recovered occasionally elsewhere in central bay.

Sample 53, obtained in very fine sand (3.20 phi units; Table 3-5; Watt, 2003) south of the Richmond-San Rafael Bridge in the vicinity of Red Rock (Figure 3-5), is the Intermediate Eastern Bay Outlier. The clustering pattern shows that this sample has characteristics of both the Shallow Eastern Bay and Intermediate Eastern Bay assemblages, although it is more closely aligned with the latter (Figure 3-4). The water depth at which the sample was obtained (16 m) lies between those of both assemblages (9 and 18 m, respectively), as does the species diversity (9 species/sample, compared to 6 and 11 species/sample, respectively). This sample has abundant *Ammonia beccarii* (40 percent) and *Trochammina inflata* (21 percent) with common *Elphidiella hannai* (16 percent) and less frequent occurrences of *Elphidium excavatum* (9 percent), *Buliminella elegantissima* (d'Orbigny) (4 percent), and *Haplophragmoides subinvolutum* (4 percent). The invasive *Trochammina hadai* is not present at this site. As with the Intermediate Eastern Bay Assemblage, the faunal assemblage of the Intermediate Eastern Bay Outlier is indicative of warm, relatively shallow subtidal estuarine conditions.

The Deep Western Bay Estuarine Assemblage is represented by the highest number of samples (15) grouped by the cluster analysis (Figure 3-4). The sample sites include 2, 3, 5, 8, 13, 14, 18, 20, 24, 27, 28, 30, 31, 32, and 46. With the exception of sample 46 located just east of the Tiburon Peninsula, all are situated in the western portion of central bay from Angel and Alcatraz Islands to the Golden Gate Bridge (Figure 3-5). Most of these samples were obtained from the Point Knox and Alcatraz Shoals (Chin and others, 2004) and range in depth from 14-49 m, averaging 23 m. Sediment grain size ranges from coarse silt to very coarse sand (Table 3-5) and averages 1.51 phi units (medium sand; Watt, 2003), reflecting extremely high average current velocity for nearly all of the tidal cycle (Figure 3-3A-D) except the slack tide (Figure 3-3E). The most abundant species in this assemblage are *Elphidiella hannai* (35 percent) and *Ammonia beccarii* (28 percent). Other common species include *Elphidium excavatum* (15 percent) and *Trochammina hadai* (9 percent). The presence of abundant cold (*Elphidiella hannai* and *Elphidium excavatum*) and warm (*Ammonia beccarii)* water species, as well as rare occurrences of species representative of the nearshore marine habitat such as *Buccella tenerrima* (Bandy), *Nonionella basispinata* (Cushman and Moyer), *Nonionella stella* Cushman and Moyer, *Rosalina globularis* d'Orbigny, *Rotorbinella turbinata* (Cushman and Valentine), and *Trichohyalus ornatissima* (Cushman) (Lankford and Phleger, 1973; McGann, 2007), suggests this is a deep subtidal estuarine assemblage that has faunal elements of both the warm shallow faunas present at intermediate depths in eastern central bay and the colder faunas of western central bay. The presence of the marine taxa is reflected in the increase in species diversity to 13 species/sample.

Seven samples (6, 10a, 22, 23, 26, 40, and 56) located at a depth of 21-60 m (averaging 29 m) on the western edge of the Point Knox Shoal, in the channel east of the Golden Gate Bridge, and west of Angel Island were grouped into the Deep Western Bay Marine Assemblage (Figures 3-4, 3-5). The sediment grain size ranged from very fine to coarse sand with shells (Table 3-5), averaging 1.34 phi units (medium sand; Watt, 2003), again reflecting very high average current velocity for all but the slack tide (Figure 3-3A-E). The foraminiferal assemblage is dominated by *Elphidiella hannai* (64 percent), *Ammonia beccarii* (14 percent) is common, and few *Elphidium excavatum* (6 percent) and *Trochammina hadai* (4 percent) are present. Because of the occurrence of such abundant *Elphidiella hannai* and numerous nearshore marine species, among them *Buccella tenerrima*, *Cassidulina limbata* Cushman and Hughes, *Cassidulina tortuosa* Cushman and Hughes, *Eggerella advena*, *Lagena striata* (d'Orbigny), *Nonionella stella*, *?Poroeponides cribrorepandus* Asano and Uchio, *Rosalina globularis*, *Rotorbinella campanulata* (Galloway and Wissler), and *Trichohyalus ornatissima*, this assemblage is considered to be a cool-water, transitional fauna between the deep subtidal estuarine and the nearshore marine environments. Similarly, Arnal and others (1980) found *Elphidiella hannai* most abundant in the coarse sediment associated with the deep channel (12-22 m) of south bay, leading them to suggest that oceanic water was present there for most of the year. This assemblage averages 11 species/sample.

Sample 11 is the Deep Western Bay Estuarine Outlier and was recovered in coarse sand (0.1 phi units; Table 3-5; Watt, 2003) at a depth of 27 m near the western edge of Alcatraz Shoal (Chin and others, 2004). With abundant *Ammonia beccarii* (24 percent) and *Elphidium excavatum* (20 percent), common *Eggerella advena* (Cushman) (19 percent) and *Elphidiella hannai* (10 percent), less abundant *Trochammina charlottensis* Cushman (9 percent), *Trochammina hadai* (6 percent), and *Buliminella elegantissima* (4 percent), and rare nearshore marine species *Buccella tenerrima*, *Lagena pliocenica* Cushman and Gray, and *Rosalina globularis*, this outlier has faunal elements characteristic of both the Deep Western Bay

Estuarine and Deep Western Bay Marine assemblages. However, because of its abundant *Elphidium excavatum* and *Eggerella advena*, the sample did not cluster with either of those assemblages and a subtidal, estuarine environment with a little marine influence is once again indicated. As discussed above, the latter is a coastal species which prefers polluted environments (Bandy and others, 1965; McGann and others, 2003). Species diversity here is the highest encountered in the study at 14 species/sample.

Fifteen samples (1, 4, 7, 12, 19, 21, 25, 29, 33, 42, 45, 48, 52, 54, and 55) were not used in the cluster analysis because fewer than 50 specimens were recovered in each (Table 3-2). Except for three samples of very fine to fine silt, these samples were among the coarsest sediment encountered in the study area, ranging from medium sand to very coarse sand with shells (0.65 phi units; coarse sand; Table 3-5; Watt, 2003). Extremely low average benthic foraminiferal number (0.1 specimens/g dry sediment) and average faunal diversity (5 species/sample) values in this coarse sediment reflects the fact that it is difficult for benthic foraminifera to reproduce and for faunas to become established in extremely high-energy environments, such as central bay, in which sediments are constantly being redeposited (Murray, 1991).

Biologic, Sedimentologic, and Anthropogenic Evidence of Sediment Transport

In addition to foraminifera, other constituents of interest were recovered in the sediment samples (Table 3-6). Among the biologic remains found were bivalve mollusks, bryozoa, crab claws, diatoms, echinoid spines, fish remains (bones, teeth and dermal plates), gastropod shells and opercula, ostracods, planktic and recrystallized foraminifera, radiolarians, seeds, spores, thecamoebians, and worm tubes. Sedimentologic remains focused on volcanic glass shards, whereas, anthropogenic-indicating remains included welding slag and microscopic beads added to paint to reduce viscosity (paint beads).

Some biologic specimens recovered are typical of estuarine environments, such as the ostracod *Cyprideis beaconensis* (LeRoy) found at 34 of 55 sites (Nichols and Thompson, 1985; Cohen and others, 2007). Several others, however, are indicators of sediment transport in central bay. For example, thecamoebians, which are tiny organisms related to foraminifera, only live in freshwater benthic environments (Scott and others, 2001). Their presence in 18 of 55 samples (2, 3, 5, 11, 13, 15, 18, 28, 31, 34, 37, 38, 39, 43, 44, 51, 53, and 56; Figure 3-6; Table 3-6) distributed widely throughout central bay illustrates how far they may be transported from a freshwater source by the strong currents that are present in most of central bay. Similarly, the presence of marsh-indicating foraminifera in six samples (3, 15, 34, 50, 51, 56; Figure 3-6; Table 3-2) recovered in nonmarsh environments as deep as 35 m are from sites where they would not normally live (McGann, 2007), once again suggesting they were transported to these locations.

Anthropogenic evidence of sediment transport within the bay involves both welding slag and paint beads. Welding slag was recovered at six sites (3, 13, 18, 22, 31, and 40; Table 3-6). Its distribution is widespread in western central bay in the vicinity of the docks on the northern side of San Francisco Bay, but also as far away as Alcatraz Island and east of Angel Island. Paint beads were also found in the sediment at six sites (13, 31, 36, 48, 49, and 50): near the northern San Francisco docks, east of Treasure Island, and east of the Tiburon Peninsula.

Not only is there evidence of sediment transport within the bay but from outside the bay as well. The presence of radiolarian and planktic foraminifera, both of marine origin (Kling, 1978; Hemleben and others, 1989), in central bay sediments is attributed to transport from the nearby ocean through the Golden Gate on the very strong flood tide (Figure 3-3C). Radiolarian occurrences are confirmed at eight sites (11, 13, 18, 28, 37, 42, 50, and 56; Figure 3-6; Table 3-6) and possibly five others. Most sites are in western central bay, but a few are located east of Angel Island and the Tiburon Peninsula. Planktic foraminifera were recovered at four sites (samples 3, 13, 27, and 53; Figure 3-6; Table 3-6); three samples from western central bay and one from as far north as the Richmond-San Rafael Bridge.

Bubble-wall shards of volcanic glass were found at 25 sites, most of which are located in western central bay (Figure 3-6; Table 3-6). Mostly clear and lesser brown-tinted forms were recovered. At this time, it is not clear whether these glass shards were primarily transported by wind or water. The source and age of these sedimentologic constituents is currently under investigation.

Comparison to Previous Studies

Of the 19 locations McDonald and Diediker (1930) studied in San Francisco Bay, seven were located within central bay. Among these are Manzanita (Marin City), Tiburon Point, Crab Cove (Corte Madera), San Quentin Point, San Pablo Point, and two sites at Fort Point off San Francisco (Figure 3-2). Although the authors did not publish faunal counts, they did identify the species obtained at each site (Table 3-7). Three species commonly found in central bay today also were recovered in their study: *Ammonia beccarii* was found at all but one of the Fort Point sites and *Elphidiella hannai* and *Elphidium* sp. were both found at four sites. Additionally, *Cibicides* sp., *Discorbis monicana* Zalesny (identified as *Rotalia rosacea* d'Orbigny), *Trochammina* sp., and a questionable occurrence of *Quinqueloculina* sp. also were found at only one or two of the seven sites.

Means' (1965) Richardson Bay study included a few samples from central bay as well: four from Raccoon Strait and four more west of Angel Island (Figure 3-2). Unfortunately, faunal counts were provided for only six of these samples (M-27 and M-28 were excluded; Table 3-7) and foraminiferal numbers (specimens/gram sediment) were listed instead of total specimen counts/sample. The two shallowest samples (2.5 m water depth; M-29 and M-30) have an abundant arenaceous fauna (62-93 percent), many representative of mudflat and marsh environments including *Ammobaculites exiguus*, *Miliammina fusca, Trochammina inflata and Trochammina macrescens*, as well as subtidal-indicating *Trochammina kellettae*, and low abundances of the calcareous species *Ammonia beccarii, Elphidium* spp., *Elphidiella hannai*, and *Buliminella elegantissima*. Similar faunal elements are present in the Shallow Eastern Bay Assemblage in the 1998 samples. Three of the four remaining samples were obtained slightly deeper (15-23 m) and are characterized by a predominantly calcareous fauna (averaging only 5 percent arenaceous) with abundant *Elphidiella hannai, Ammonia beccarii, Elphidium excavatum*, and the addition of *Elphidium bartletti* Cushman, as well as a few marine-indicating species [*Buccella tenerrima, Fissurina marginata* (Montagu), and *Rosalina globularis*], suggestive of the 1998 Deep Western Bay Estuarine Assemblage. Sample M-31 is transitional between these two groups, both in depth (~10 m) and faunal composition, and it consists of 30 percent arenaceous taxa, as well as abundant calcareous forms found in the three deeper samples.

Because total specimen counts for each sample were not reported by McDonald and Diediker (1930) or Means (1965), neither of their studies could be used for quantitative comparisons. Instead, the results obtained by the central bay studies of Locke (1971), Wagner (1978), and Sloan (1980-1981, unpublished data), as well as 40 samples from the present (1998) central bay study, were subjected to cluster analysis to compare the foraminiferal distributions in the latter half of the 20th century.

Generally, the 1998 samples clustered together in a similar pattern to that resulting from the samples being analyzed by themselves (compare Figures 3-4 and 3-7). However, two additional clusters are evident as well. The largest grouping includes seven of Locke's (1971) samples from Point San Pablo to the Richmond-San Rafael Bridge, the two samples of Sloan's 1980-1981 site from the shallow waters south of the Berkeley Pier, as well as sample 53 from the 1998 study. Sample 53 was identified as the Intermediate Eastern Bay Outlier in the previous cluster. The presence of this outlier sample, as well as a combined shallow-depth arenaceous and intermediate-depth calcareous foraminiferal fauna in the other samples (Table 3-7) suggests this is a transitional assemblage with characteristics of both the Shallow Eastern and Intermediate Eastern Bay Assemblages.

Wagner's (1978) three grab samples obtained in the deep waters between Alcatraz Island and the Golden Gate Bridge grouped together to form the last cluster (Figure 3-7). These samples are characterized by abundant *Elphidiella hannai* (9-43 percent; Table 3-7) and common *Elphidium*, represented by numerous species. *Ammonia beccarii* occurs in low abundance (2-14 percent), whereas *Trochammina kellettae* comprises as much as 26 percent of the fauna. Marine-indicating species also are present, including *Buccella tenerrima*, some species of *Trochammina*, and *Rosalina globularis* (1-49 percent). With a mixture of deep estuarine and marine faunal elements, this assemblage appears to be transitional between the Deep Western Bay Estuarine and Deep Western Bay Marine Assemblages.

The cluster analysis also identified one additional outlier, Locke's sample L-32 (Figure 3-7). This sample has a unique assemblage of only three species: 68 percent *Ammonia beccarii* and 16 percent of both *Elphidiella hannai* and *Bolivina* sp. (Table 3-7). The abundances of the first two species are similar to those characteristic of the Intermediate Eastern Bay Assemblage, but no sample recovered from central bay from 1961 to 1998 has more than 2 percent *Bolivina*.

Introduced Foraminifera *Trochammina hadai*

The invasive foraminifera *Trochammina hadai* is thought to have been introduced into San Francisco Bay in the early 1980s which is supported by the fact that there is no evidence of the species in samples collected from the estuary before 1983 (McGann and others, 2000). Fifteen years later, however, *Trochammina hadai* had already spread throughout the brackish regions of the estuary: to the eastern edge of San Pablo Bay in north bay and to the extreme southern limit of south bay (McGann and Sloan, 1999). In the 1998 central bay sites, the species dominated the fauna of the shallow depths (Shallow Eastern Bay Assemblage; 68-97 percent, averaging 77 percent; Table 3-2), the environment in which it also thrives in Japan and elsewhere along the eastern Pacific seaboard (McGann and others, 2000). It continued to be a significant component of the Intermediate Eastern Bay Assemblage as well (7-51 percent, averaging 28 percent). The abundance of *Trochammina hadai* dropped significantly in the deeper waters west of Alcatraz Island though, averaging only 4-9 percent of the assemblage. Although the 1998 samples were not stained and therefore it is impossible to confirm, it is assumed that the specimens recovered at these deep stations were not living when collected but had been transported there after death.

Conclusions

In this study, the distribution of foraminifera have been described from samples obtained in 1998 in the subembayment of San Francisco Bay known as central bay. Of the most common native species recovered, *Ammonia beccarii* was most abundant in the warmer water at intermediate depths in central bay, *Elphidium excavatum* appeared to prefer the cooler conditions surrounding Alcatraz Island, and *Elphidiella hannai* was associated with the cold marine water in western central bay. Just 15 years after its introduction, the nonnative species *Trochammina hadai* dominated the warmest and shallowest eastern regions of the bay, comprising 68-98 percent of the fauna. Four distinct assemblages were recognized, reflecting the intensity of the tidal flow, water temperature, and the degree of marine influence. The presence of allochthonous biologic and anthropogenic constituents, as well as sediment grain size, were used to assess sediment transport. In the future, the availability of stained samples would lead to a better understanding of the degree to which foraminifera and other biological constituents are transported in central bay.

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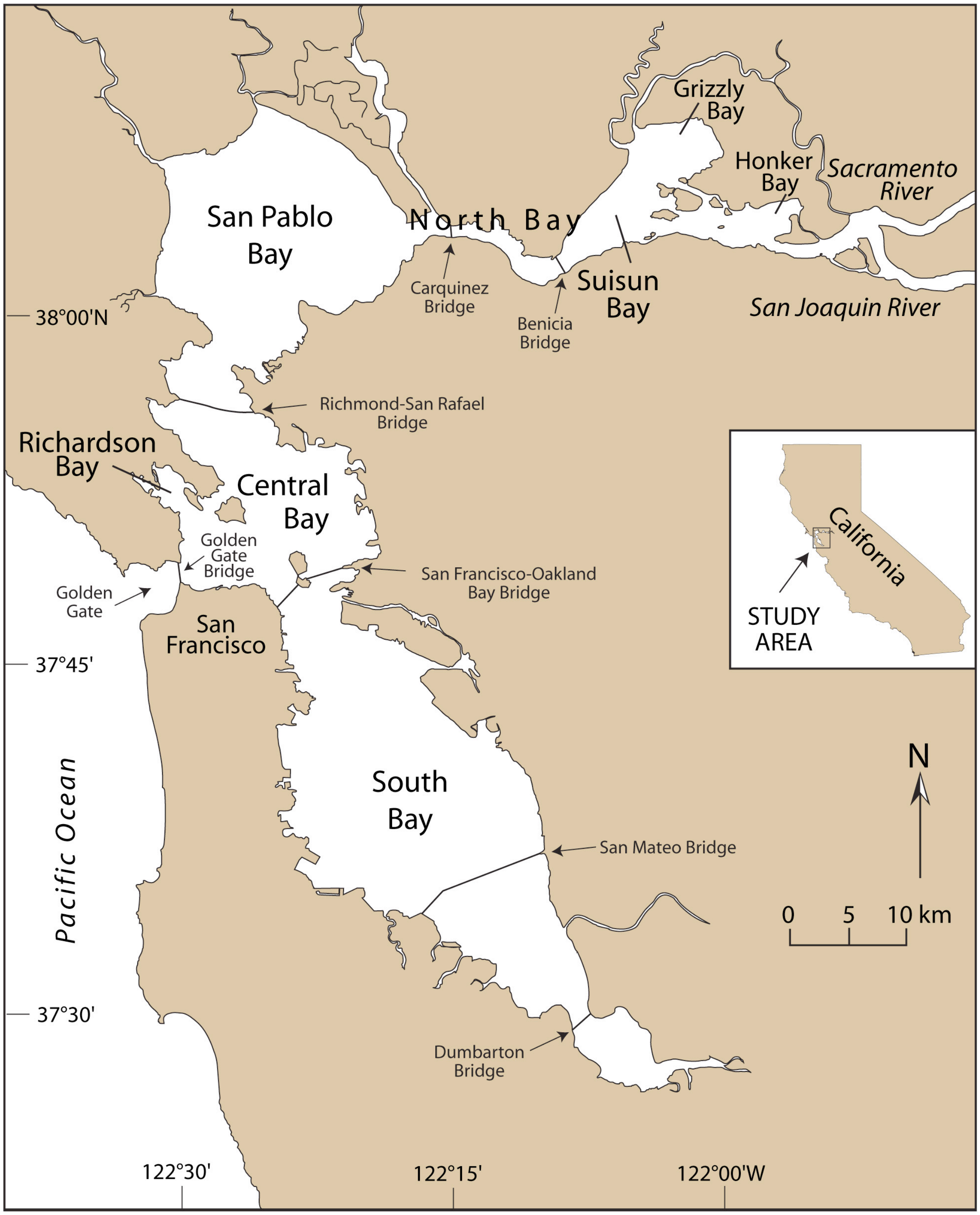

Figure 3-1. Location map of San Francisco Bay, California, including the three subembayments: north bay (including San Pablo, Suisun, Grizzly, and Honker Bays), central bay (including Richardson Bay), and south bay.

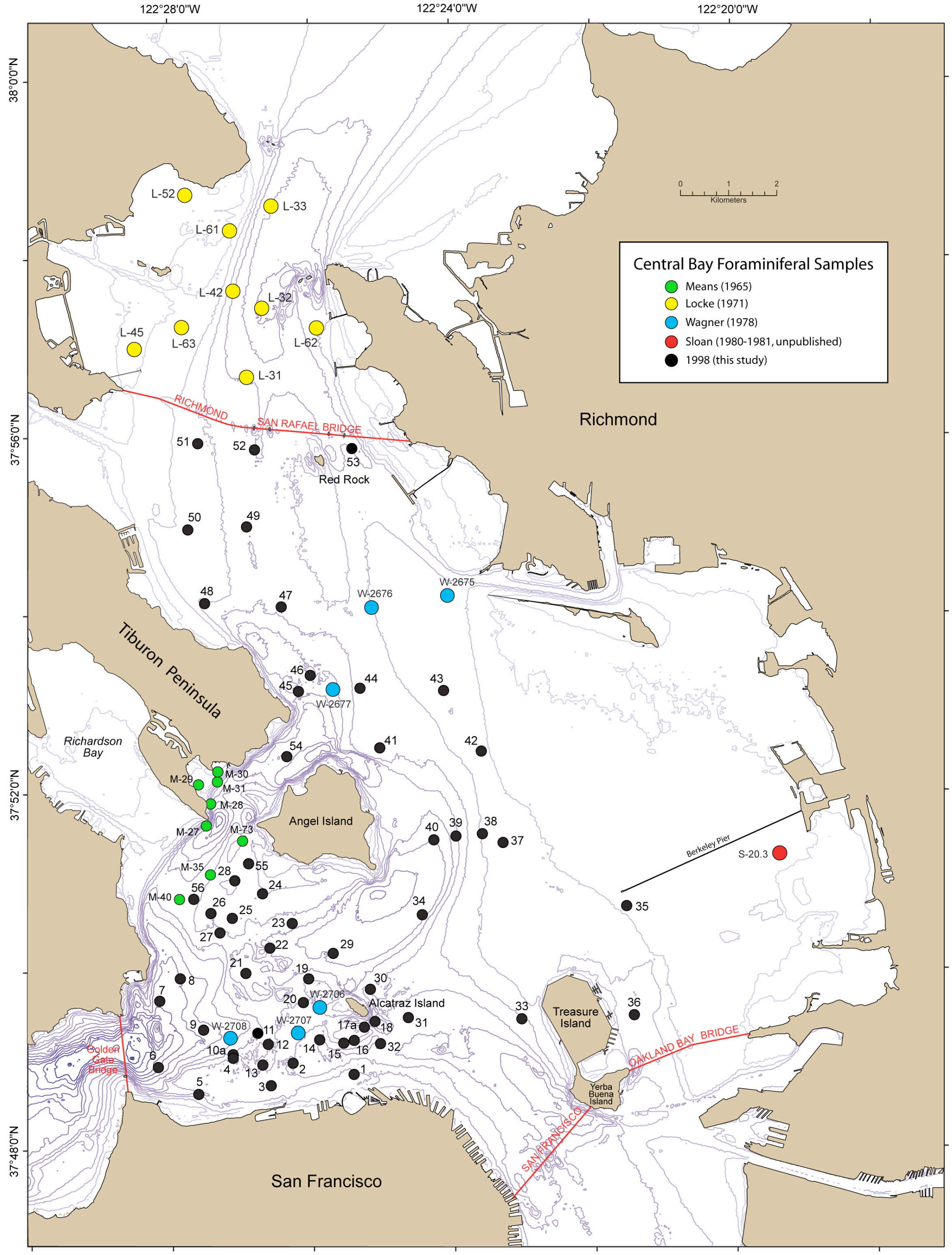

Figure 3-2. Location of the foraminiferal study sites in central San Francisco Bay, California. Sites includes those collected in 1998 (this study), as well as those of Means (1965), Locke (1971), Wagner (1978), and Sloan (1980-1981, unpublished data). Bathymetric contours in meters.

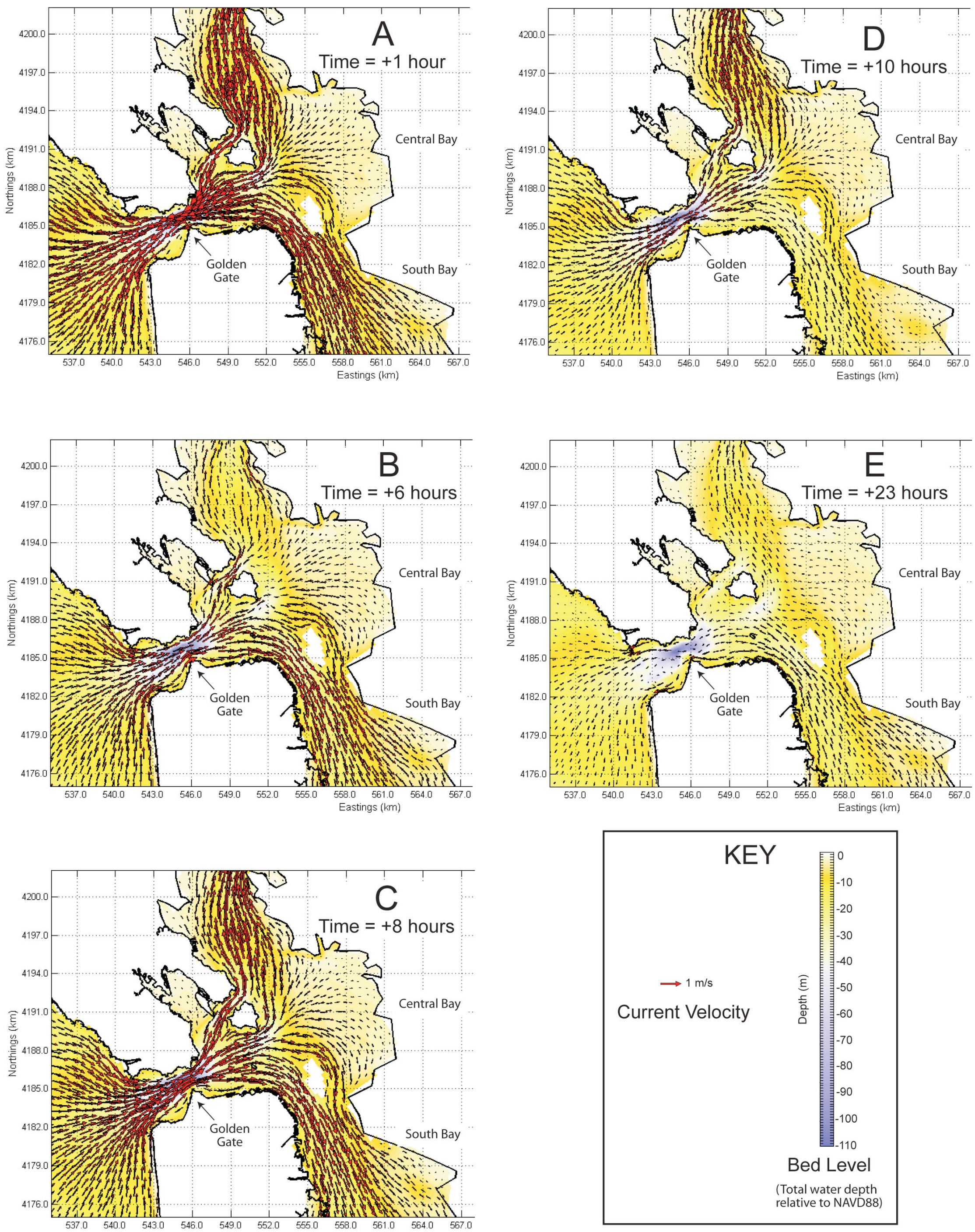

Figure 3-3. Time series of tidal currents flowing between the marine realm off central California and two of the three embayments (central and south bays) of San Francisco Bay. Figures courtesy of Li Erikson (USGS), modifed from Barnard and others (2008).

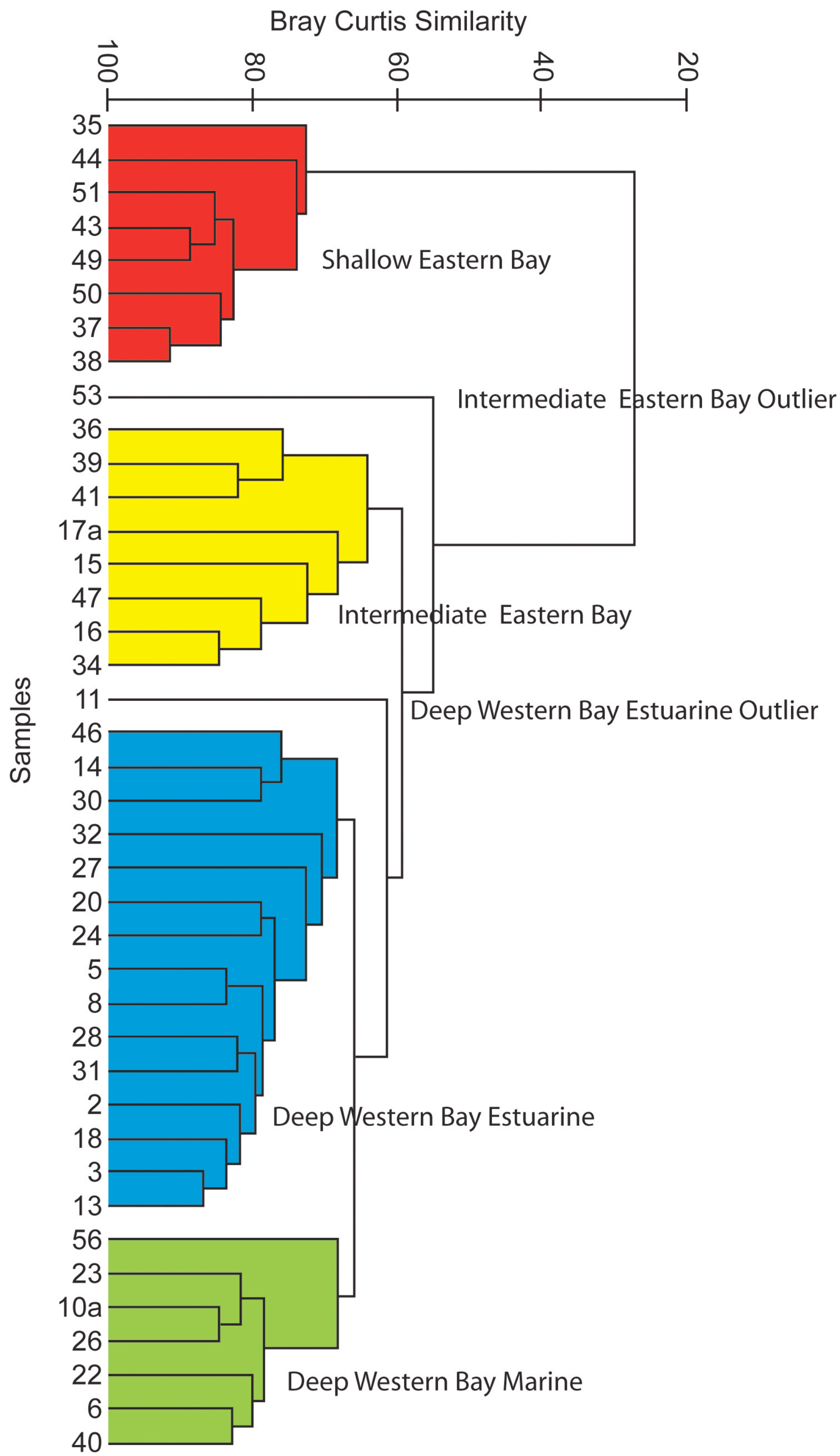

Figure 3-4. Dendogram of the Q-mode cluster analysis of the 1998 central San Francisco Bay samples based on the quantitative (percent frequencies) foraminiferal abundances. Four assemblages and two outliers are recognized.

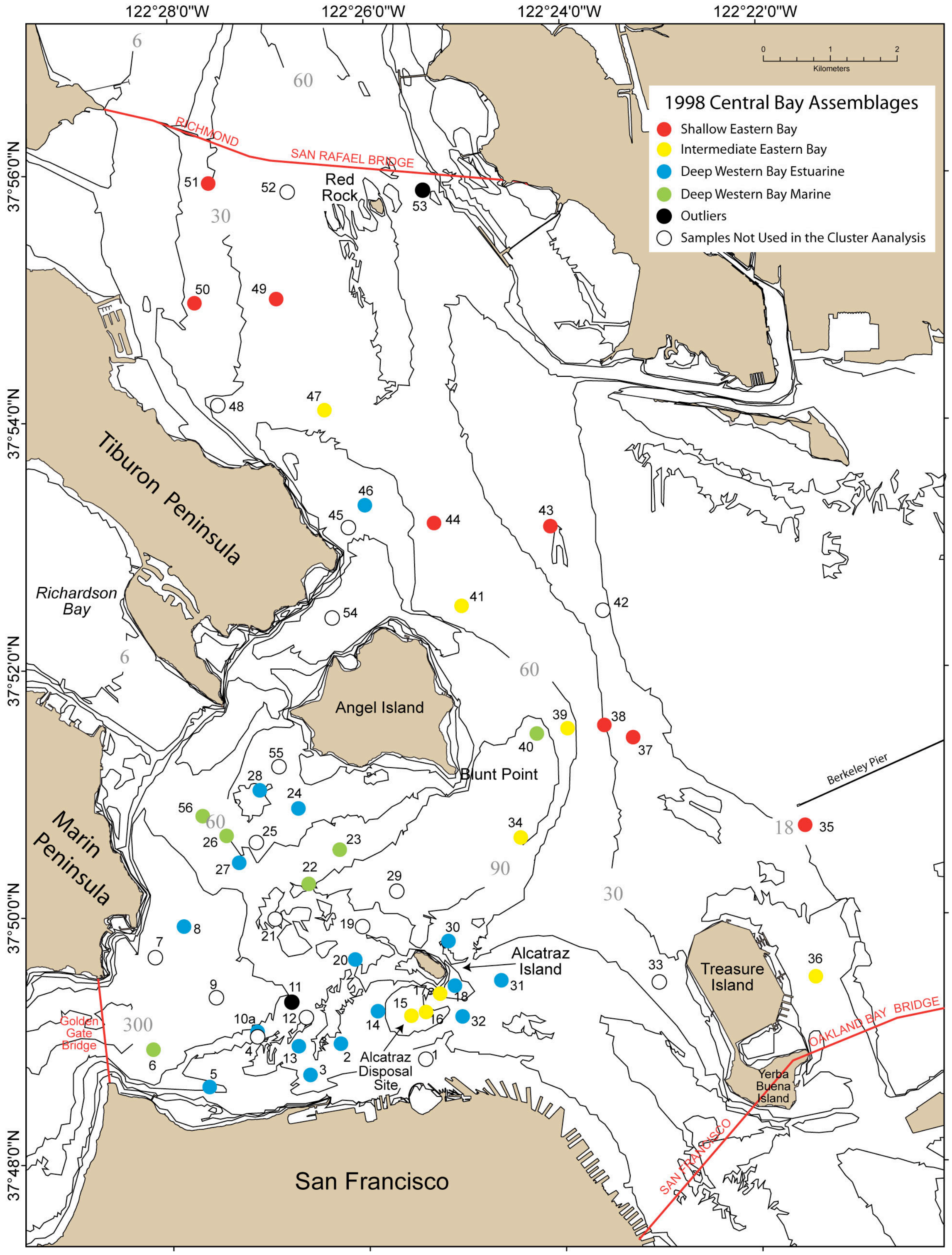

Figure 3-5. Spatial distribution of the 1998 central San Francisco Bay foraminiferal assemblages.

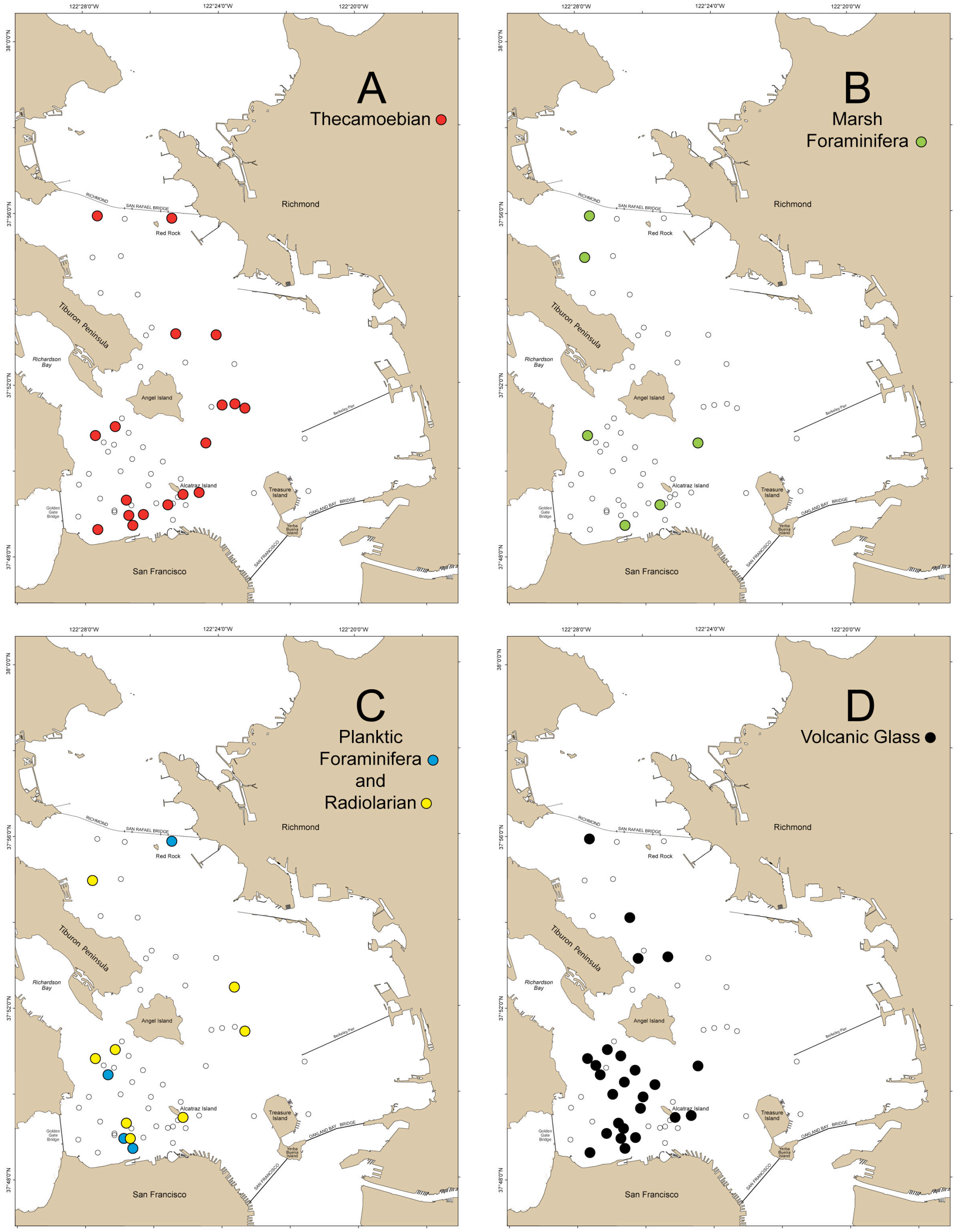

Figure 3-6. Spatial distribution in the 1998 central San Francisco Bay samples of *A*, fresh water-indicating thecamoebians, *B*, brackish water-indicating marsh foraminifera, *C*, marine-indicating planktic foraminifera and radiolarian, and *D*, transported volcanic glass. Sites with constituents present enlarged to enhance visibility.

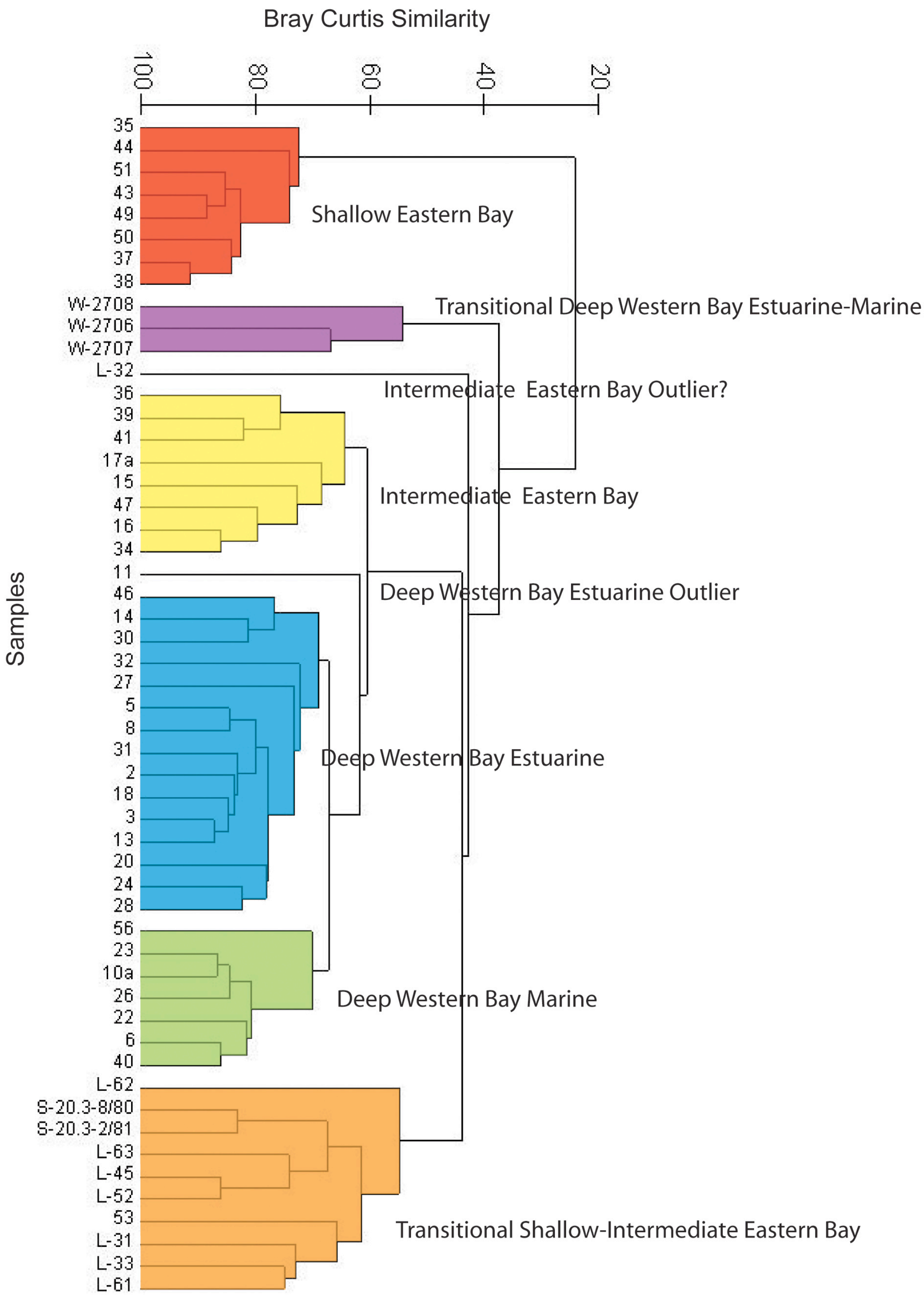

Figure 3-7. Dendogram of the Q-mode cluster analysis of the 1971-1998 central San Francisco Bay samples based on the quantitative (percent frequencies) foraminiferal abundances. Sites includes those collected in 1998 (this study), as well as those of Locke (L-; 1971), Wagner (W-; 1978), and Sloan (S-; 1980-1981, unpublished data). Six assemblages and two outliers are recognized.

Tables 3-1 through 3.7 are spreadsheet files in http://pubs.usgs.gov/of/2010/1130/of2010-1130_table3 in several formats.

Table 3-1. Sample number, water depth (m), and location (latitude and longitude) of the sampling sites of the 1998 central San Francisco Bay study (USGS cruise J-1-98-SF).

Table 3-2. Benthic foraminifera identified in the 1998 central San Francisco Bay samples (in bold) and species and synonomies used in the studies of McDonald and Diediker (1930), Means (1965), Locke (1971), Wagner (1978), and Sloan (1980-1981, unpublished data).

Table 3-3. Species abundances of the benthic foraminifera in the 1998 central San Francisco Bay samples, given as a percentage of total foraminifera/sample.

Table 3-4. 1998 central San Francisco Bay foraminiferal cluster assemblages, number of samples in cluster, depth range and average depth (in meters), representative species, percentage abundance range and average percentage abundance, and ecological interpretation. Dominant species (average abundance 20 percent or greater) highlighted in yellow.

Table 3-5. Water depth (m), sample weight, total foraminifera counted, benthic foraminiferal number, faunal diversity, cluster assemblage, sediment grain size and sediment size class of the 1998 central San Francisco Bay samples.

Table 3-6. Other constituents in the 1998 central San Francisco Bay samples.

Table 3-7. Abundances of benthic foraminifera in central San Francisco Bay samples collected from 1930-1981. Presence/absence given in McDonald and Diediker (1930), and percentage of total foraminifera per sample in those collected by Means (1965), Locke (1971), Wagner (1978), and Sloan (1980-1981, unpublished data). Samples marked with an asterisk are adjusted for removal of planktic foraminiferal specimens. No faunal counts were reported by Means for samples M-27 and M-28 or by Wagner for samples W-2675, W-2676, and W-2677. Depth of Means' samples approximated based on bottom topography map (Means, 1965) and recent USGS bathymetric investigations (this report).