STATE OF CALIFORNIA
REGIONAL WATER QUALITY CONTROL BOARD
SAN FRANCISCO BAY REGION

STAFF SUMMARY REPORT (Elizabeth Christian)
MEETING DATE: May 13, 2015

ITEM: **8**

SUBJECT: **U. S. Army Corps of Engineers, San Francisco District –** Adoption of Reissued Waste Discharge Requirements and Clean Water Act Section 401 Certification for 2015-2019 Maintenance Dredging Program

CHRONOLOGY: 2007 – Waste Discharge Requirements for Maintenance Dredging Program adopted

DISCUSSION: The Revised Tentative Order (Appendix A) would reissue Waste Discharge Requirements (WDRs) and Water Quality Certification for the Army Corps' 2015-2019 maintenance dredging program for the federal navigation channels in San Francisco Bay. Adoption of this Revised Tentative Order (Order) can only be considered after the Board has certified the program's EIR in Item 7 on this meeting's agenda.

Background

The Corps' maintenance dredging program involves 11 federal navigation channels, including the dredging activity itself, disposal of dredged material in the Bay at four designated disposal sites, and beneficial reuse of dredged material consisting of beach nourishment offshore of San Francisco's Ocean Beach. Beneficial reuse projects that use the Corps' dredged material, including restoration of tidal marsh habitat along the Bay margin and levee maintenance, are regulated under separate Board-adopted orders issued to each project site.

The Order's requirements include:

1) Limiting disposal of dredged material at in-Bay disposal sites consistent with the goals of the Long-Term Management Strategy (LTMS) for the placement of dredged material in the San Francisco Bay Region. Because the Corps is the largest dredger in the Bay Region and maintains administrative control over use of designated aquatic disposal sites by all dredgers, the Order requires the Corps to manage disposal at those sites in accordance with LTMS' 1.25 million cubic yard annual disposal goal set forth in the Basin Plan.

2) Reduction of hydraulic suction hopper dredge use in the Bay, starting in 2017, to fully address potentially significant impacts of hydraulic dredging, i.e., entrainment of fish species listed as threatened or endangered under State and federal endangered species acts. This requirement is phased in due to the Corps' budgetary process. Implementation of other measures to avoid, minimize, and mitigate entrainment impacts are required to be implemented immediately.

3) Evaluation of sediment suitability for the proposed placement sites coordinated through the multi-agency Dredged Material Management Office (of which the Board is a member) for each proposed dredging episode.

4) Analysis of alternatives to aquatic disposal of dredged sediments pursuant to section 404(b)(1) of the Clean Water Act prior to approval of dredging and disposal episodes.

5) Water quality monitoring for discharges of water entrained with the dredged sediment (i.e., overflow or decant water) back to the Bay from barges during mechanical (clamshell bucket) dredging. This discharge may contain high concentrations of fine-grain suspended sediment, which can greatly increase turbidity in the vicinity of the dredge operation. In the past, this discharge has been prohibited. The Order removes the prohibition in specific circumstances but requires monitoring to ensure there is no water quality impact.

The initial tentative order was circulated for a 30-day public comment period on March 20, 2015. We received comments (Appendix B) from the Corps, San Francisco Baykeeper (Baykeeper), California Marine Affairs and Navigation Conference (CMANC), R.E. Staite Engineering, Inc., and the Port of Redwood City. All of the comments are addressed in the Response to Comments (Appendix C).

The most significant comments were received from the Corps who does not agree that its project is subject to State requirements under the Water Code or WDRs; as such, it is only requesting a Water Quality Certification under the Clean Water Act (CWA). Several of the Corps' comments challenged both the Board's legal authority to regulate the act of dredging (vs. "discharge" of dredged material) under both CWA section 401 and the Water Code and the Board's authority to protect species listed under State and federal endangered species acts. The Corps also argued that the reduced hopper dredging requirement is infeasible to implement due to limitations imposed by the "federal standard" regulation and could lead to deferred dredging.

We disagree with the Corps' legal arguments in its comments. The Board has been issuing WDRs to the Corps for its navigational channel maintenance program since 1990, so we disagree with the Corps about any lack of authority to issue WDRs and or to regulate dredging to lessen the water quality and environmental impacts, including fish entrainment, of the dredging activities. We have provided a detailed response to these comments in Appendix C explaining the State perspective and have made no significant changes to the Order.

Baykeeper raised concerns about the Order's allowance of dredged material disposal in the ocean in light of the observed reduction in sediment supply to the Bay system. We provided our understanding of these issues in Appendix C and explained that the Order does not authorize ocean disposal and cannot require a full analysis of Ocean Dumping Criteria because U.S. EPA regulates ocean disposal outside of the three-mile limit to waters of the State in the ocean.

In general, revisions to the Order consisted of non-substantive modifications to update language, add to existing information, or clarify language in the Order, correct typographical errors, and make minor editorial and formatting changes. One staff initiated change is reflected in Appendix C.

RECOMMEN-DATION:	Adoption of the Revised Tentative Order
Appendices:	A. Revised Tentative Order B. Comments Received; San Francisco Baykeeper comment letter attachments available at http://www.waterboards.ca.gov/sanfranciscobay/board_info/agendas/2015/May/5_13_Agenda.pdf C. Response to Comments

APPENDIX A

Revised Tentative Order
Reissued Waste Discharge Requirements
and Water Quality Certification

CALIFORNIA REGIONAL WATER QUALITY CONTROL BOARD
SAN FRANCISCO BAY REGION

REVISED TENTATIVE ORDER

REISSUED WASTE DISCHARGE REQUIREMENTS and WATER QUALITY CERTIFICATION for:

U.S. ARMY CORPS OF ENGINEERS, SAN FRANCISCO DISTRICT MAINTENANCE DREDGING PROGRAM, 2015 THROUGH 2019

The California Regional Water Quality Control Board, San Francisco Bay Region (Water Board), finds that:

Purpose

1. This Order constitutes Waste Discharge Requirements (WDRs) and Water Quality Certification (Certification) for the U.S. Army Corps of Engineers, San Francisco District's (USACE) federal navigation channel maintenance dredging program in the San Francisco Bay Area and for disposal of dredged material created by these activities over a five-year period. The first two years of the project continue USACE's current maintenance dredging program in terms of equipment type. Starting in 2017, to fully address potentially significant impacts of hydraulic dredging, i.e., entrainment of fish species listed as threatened or endangered under State and federal endangered species acts, this Order conditions dredging activities to reduce the use of hydraulic suction hopper dredges in San Francisco Bay.

Scope

2. USACE maintains the navigability of federally-authorized channels at the entrance to and in San Francisco Bay. USACE removes accumulated sediment (primarily silt and clay) by hydraulic (e.g., self-propelled hopper, hydraulic cutter head) or mechanical (e.g., clamshell) dredges and typically disposes of the dredged material by either self-propelled hopper, dump scow, or by use of a pipeline to transport material to beneficial reuse sites.

3. This Order applies only to maintenance dredging, which is performed on a periodic basis to previously authorized depths and removes recently deposited materials. This Order does not apply to "new work" dredging, which removes material to new authorized depths and may involve dredging consolidated materials or historically-contaminated materials.

4. For the five-year period covered by this Order, USACE proposes to perform maintenance dredging at several locations in the Bay Area (Figures 1 - 11). Based on the range of volumes that USACE has proposed for planning purposes over the next five years (Table 1), the maximum total dredging volume within San Francisco Bay is 12.4 million cubic yards (mcy) and the maximum total dredging volume in the San Francisco Main Ship Channel (MSC) west of the Golden Gate, outside San Francisco Bay is 2.5 mcy.

Long Term Management Strategy for Disposal of Dredged Material

5. The Water Board and USACE are agencies that participate in the Long Term Management Strategy (LTMS) for the Placement of Dredged Material in the San Francisco Bay Region. Other agencies participating in LTMS are U. S. EPA, the San Francisco Bay Conservation and Development Commission (BCDC), and the California State Lands Commission (CSLC). These LTMS agencies evaluated alternative management options for disposal and reuse of dredged sediment over a 50-year planning horizon in a Policy Environmental Impact Statement/Programmatic Environmental Impact Report (EIS/EIR) completed in October 1998. The EIS/EIR indicated that dredged material disposal may have adverse impacts on the beneficial uses of the waters of San Francisco Bay and that in-Bay disposal should be reduced from historical levels.

6. The LTMS agencies determined that the preferred alternative is to reduce disposal in the Bay to a long-term average of 1.25 mcy or less per year, with approximately 80 percent of dredged sediment to be targeted for beneficial reuse or out-of-Bay disposal and only 20 percent targeted for in-Bay disposal. This long-term goal can be accomplished by maximizing beneficial reuse of dredged material suitable for habitat restoration along the Bay margins and disposing suitable dredged material outside the Bay only when beneficial reuse is not practicable. As the science and knowledge regarding climate change and the resulting increase in sea level rise has grown, it is now recognized that the low-lying areas of the Bay, which were once historical marshes, are in jeopardy of being inundated both by increasing sea level and through storm surges that are occurring more frequently and at greater intensity than previously experienced. In addition, in the mid-2000s, scientists from the U.S. Geological Survey identified a significant reduction in suspended sediment loading from the Sacramento-San Joaquin river system. Less sediment in suspension and circulation within the Bay impairs the ability of shorelines, mudflats, and tidal wetlands to withstand erosion and inundation, especially as sea level rises. The Water Board therefore finds that it is in the public interest to encourage beneficial reuse of suitable dredged material as one component of regional adaptation to climate change and reduced suspended sediment loading to the Bay.

7. Specific guidance for implementing the LTMS long-term goal of reduced in-Bay annual disposal goal of 1.25 mcy or less is described in the LTMS Management Plan (Management Plan), approved in July 2001 by the LTMS Executive Committee. To allow time for planning, budgeting, and creating alternatives to in-Bay disposal, the Management Plan established a 12-year transition period for achieving the long-term goal. The transition period’s disposal volume limits were voluntary as long as in-Bay goals were met overall. Public assurance that in-Bay disposal would in fact decrease was provided by strict volume allocations to individual dredgers that could be triggered if goals were not met. The transition period successfully concluded in 2012 with in-Bay disposal targets met every three years as described in the Management Plan.

   USACE is the largest dredger in the Bay Area. Efforts by USACE to reduce in-Bay disposal are critical to successful implementation of the LTMS long-term goal. In keeping with the LTMS long-term goal, USACE must reserve sufficient monthly capacity at in-Bay sites for smaller non-Corps projects. The 1.25 mcy annual in-Bay disposal goal allocates 250,000 cy/year to “small” dredging projects, defined in the

Management Plan as those projects that generate less than 50,000 cy per year on average with a design depth of less than -12 feet MLLW, leaving the remaining 1.0 mcy of the disposal goal plus the 0.25 mcy "contingency volume" to be split between USACE and the medium-sized maritime industry dredgers. USACE's average in-Bay disposal volume for 2015 through 2019 is expected to be within 0.625 – 0.750 mcy per year (50 to 60 percent of the 1.0 mcy in-Bay disposal goal plus the 0.25 mcy contingency volume it shares with other dredgers). The total not to exceed in-Bay disposal volume for this Order is 3.5 mcy (calculated as 0.7 mcy times five years). Further action by the Water Board will be required for in-Bay disposal in excess of this quantity.

Dredging Projects Summary

8. USACE's maintenance dredging program provides for maintenance of 11 federal navigation channels in the San Francisco Bay, including six channels dredged annually and five channels with non-annual dredging cycles. These 11 channels have a combined surface area of 5,699 acres, which equates to 2.22 percent of the total surface area of San Francisco Bay. During each fiscal year from 2015 to 2019, USACE plans to dredge the seven channels most critical to the region's maritime trade and to regional and national economies: Oakland Harbor, Richmond Outer Harbor, Richmond Inner Harbor, Suisun Bay and New York Slough, Pinole Shoal (San Pablo Bay), Redwood City Harbor (not including the San Bruno Channel), and San Francisco MSC. Other channels that USACE may dredge at some point during the next five years, if funding becomes available, include the San Rafael (Inner) Canal and Across the Flats, the Napa River (upper and lower reaches), Petaluma River (upper portion and Across the Flats), the Brooklyn Basin (South Channel) portion of Oakland Harbor, San Bruno Channel, and San Leandro Marina (Jack D. Maltester) Channels. Each of these channels is either due or overdue for dredging.

The general locations of the channels are depicted collectively in Figure 1. The channel boundaries are more precisely shown on the project maps provided in Figures 2 - 11. Since this Order is a five-year WDR/Certification, the actual shoaling locations are not yet known. Dredging will be confined within the channel boundaries shown in Figures 2 - 11 and shall not exceed the project depth, as shown in Table 1, plus an over dredge depth of 2 feet. Placement of dredge material will be confined to the boundaries of the placement sites depicted in Figures 1 - 11.

Table 1 summarizes USACE's 2015 - 2019 dredging program, including maximum dredging volumes, the Water Board's preferred placement sites, the federal standard placement sites, and alternate placement sites. The volume estimates are based on historical data.

Placement Sites for Dredged Material

9. It is LTMS' goal that sediment dredged from San Francisco Bay be beneficially reused for a variety of purposes such as wetland creation, levee maintenance, or construction fill. Existing beneficial reuse sites include: the Montezuma Wetlands Restoration Project (regulated by Water Board Order No. R2-2012-0089), the Cullinan Ranch Restoration Project (regulated by Water Board Order No. R2-2010-0108), and Winter Island levee maintenance (Figures 1, 5, 6, and 8). At their own discretion, dredging contractors or the project sponsors may propose to use other permitted upland locations. All necessary

environmental documentation must be completed for a site prior to it receiving any dredged material.

Disposal in the Bay consistent with the goal occurs at four designated aquatic disposal sites (Figure 1): the Alcatraz Island Disposal Site (SF-11), the San Pablo Bay Disposal Site (SF-10), the Carquinez Strait Disposal Site (SF-09), and the Suisun Bay Disposal Site (SF-16). Ocean disposal for Bay dredged material occurs at the San Francisco Deep Ocean Disposal Site (SF-DODS), about 55 miles (48 nautical miles) west of the Golden Gate and thus beyond the three mile offshore limit of Water Board jurisdiction. Under the federal Marine Protection, Research and Sanctuary Act, U.S. EPA must concur with disposal at SF-DODS.

Sand dredged from the San Francisco MSC may be placed for beneficial reuse (nourishment of the San Francisco littoral cell to help combat erosion at Ocean Beach) at the easternmost portion of the San Francisco Bar Disposal Site (SF-8) (Figure 2), within the three nautical mile limit of Water Board jurisdiction. Pre-site-designation studies concluded that the area would be dispersive, meaning that waves would spread the sand shoreward to the surf zone and beach at such a rate that accumulation would be minimal. However, surveys indicate that spreading occurs at a much slower rate than expected and that underwater shoals impair safe operation of hopper dredges during rough seas. USACE therefore limits use of SF-8 to the extent feasible. USACE is currently conducting a beach nourishment beneficial reuse pilot demonstration study at the Ocean Beach Demonstration Site (OBDS), which is encompassed by the future SF-17 placement site, in waters of the Pacific Ocean adjacent to the south-of-Sloat-Boulevard stretch of Ocean Beach (Figure 2). The OBDS is located where waves can potentially feed sediment toward the southern reach of Ocean Beach, which may ultimately help mitigate ongoing shoreline erosion in the area that threatens significant municipal infrastructure, including segments of the Great Highway and major sewer lines running underneath and alongside it. SF-17 is in the process of being formally designated as a disposal site under section 404 of the Clean Water Act.

Table 1. 2015 – 2019 Dredging Project Summary

Channel	Authorized or Regulatory Depth (feet below MLLW)[1]	Dredge Type	Typical Dredging Frequency (years)	Planning Volume per Dredge Episode (cy)	Water Board Preferred Placement Site	Federal Standard Placement Site[2]	Placement Site Alternate 1[3]	Placement Site Alternate 2[3]
Richmond Inner Harbor	41	Clamshell-Bucket	annual	350,000 – 400,000	Habitat Restoration Beneficial Reuse	SF-DODS	Upland Beneficial Reuse	Other In-Bay Site
Outer Harbor	45	Hopper*/Clamshell-Bucket	annual	150,000 – 250,000	Habitat Restoration Beneficial Reuse	SF-11	Other In-Bay Site	Upland Beneficial Reuse
Oakland Inner and Outer Harbor	50	Clamshell-Bucket	annual	350,000 – 700,000	Habitat Restoration Beneficial Reuse	SF-DODS	Upland Beneficial Reuse	In-Bay Site
Pinole Shoal		Hopper*/Clamshell-Bucket	annual	150,000 – 200,000	Habitat Restoration Beneficial Reuse	SF-10	Other In-Bay Site	Upland Beneficial Reuse
Suisun Bay Channel and New York Slough[4]	35	Hopper/Clamshell-Bucket starting in 2017	annual	175,000 – 200,000	Habitat Restoration Beneficial Reuse	SF-16	Other In-Bay Site	Upland Beneficial Reuse
Bulls Head[5] Reach	39							
Redwood City Harbor	30	Clamshell-Bucket (Harbor Channels) Hopper (San Bruno Channel)	1-2	300,000 – 600,000	Habitat Restoration Beneficial Reuse	SF-11	Other In-Bay Site	Upland Beneficial Reuse except for San Bruno Channel; SF-DODS for San Bruno Channel

Channel	Authorized or Regulatory Depth (feet below MLLW)[1]	Dredge Type	Typical Dredging Frequency (years)	Planning Volume per Dredge Episode (cy)	Water Board Preferred Placement Site	Federal Standard Placement Site[2]	Placement Site Alternate 1[3]	Placement Site Alternate 2[3]
Petaluma River Channel (and Across the Flats^)	8	Cutterhead-Pipeline (River Channel) Clamshell-Bucket (Across the Flats)	4-7	150,000	Upland (Sponsor Provided) for the River Channel; Habitat Restoration Beneficial Reuse for Across the Flats	Upland (Sponsor Provided) for the River Channel; SF-10 for Across the Flats	Upland Beneficial Reuse	Other In-Bay Site
Napa River Channel^ Mare Island Strait Causeway to Asylum Slough	15	Cutterhead-Pipeline	6-10	140,000	Upland (Sponsor Provided) or Habitat Restoration Beneficial Reuse	Upland (Sponsor Provided)	Other Upland Site	SF-9 for downstream reach only
Napa River Channel^ Asylum Slough to Third Street	10							
San Rafael Creek Channel - Across the Flats	8	Clamshell-Bucket	4-7	87,000 – 150,000	Habitat Restoration Beneficial Reuse	SF-11	Other In-Bay Site	Upland Beneficial Reuse
San Rafael Creek Channel – Inner Canal	6							
San Leandro Marina (Jack D. Maltester Channel)	8	Cutterhead-Pipeline	4-6	121,000 – 187,000	Habitat Restoration Beneficial Reuse	Upland (Sponsor Provided such as San Leandro DMMS)	In-Bay Site	Upland Beneficial Reuse

Channel	Authorized or Regulatory Depth (feet below MLLW)[1]	Dredge Type	Typical Dredging Frequency (years)	Planning Volume per Dredge Episode (cy)	Water Board Preferred Placement Site	Federal Standard Placement Site[2]	Placement Site Alternate 1[3]	Placement Site Alternate 2[3]
San Francisco Bay 5-Year Maximum Dredge Volume: 12.4 mcy[6]								
San Francisco Harbor – Main Ship Channel	55	Hopper	annual	350,000 – 500,000	Ocean Beach Onshore	SF-8	SF-17	Ocean Beach Onshore
Main Ship Channel 5-Year Maximum Dredge Volume: 2.5 mcy								

Notes:

* Both Richmond Outer Harbor and Pinole Shoal could not be dredged with a hopper in the same year beginning in 2017 - see Provision 10.

^ For areas not dredged since 2000, the last dredging event is reported.

1 2-foot overdredge allowance not shown.

2 The federal standard is defined as the least-costly dredged material disposal or placement alternative consistent with sound engineering practices, and meeting the environmental standards established by the 404(b)(1) evaluation process or ocean dumping criteria (33 C.F.R. § 335.7).

3 USACE cannot use placement sites until NEPA and/or CEQA environmental review and acquisition of required environmental approvals from resource and regulatory agencies is completed.

4 Aside from regularly scheduled maintenance of this navigation project, USACE would take urgent action outside the work window, as needed, to remove the hazardous shoaling at Bulls Head Reach.

5 Because of rapid shoaling at Bulls Head Reach, this portion of the Suisun Bay Channel may be advance maintenance dredged by up to 4 feet, plus an additional 2 feet of allowable overdepth.

6 Assumes Redwood City Harbor is dredged annually and that the smaller, non-annual projects: Napa River Channel, Petaluma River Channel, San Rafael Creek Channel, and San Leandro Marina Channel, are dredged once each during 2015-2019.

CEQA = California Environmental Quality Act
cy = cubic yards
mcy = million cubic yards
NEPA = National Environmental Policy Act
Ocean Beach Onshore = Onshore Ocean Beach placement site
San Leandro DMMS = Upland San Leandro Dredged Material Management Site
SF-8 = San Francisco Bar Channel Disposal Site (ocean site)
SF-9 = Carquinez Strait placement site (in-Bay site)
SF-10 = San Pablo Bay placement site (in-Bay site)
SF-11 = Alcatraz Island placement site (in-Bay site)
SF-16 = Suisun Bay placement site (in-Bay site)
SF-17 = Ocean Beach placement site (near shore site, includes the Ocean Beach demonstration site)
SF-DODS = San Francisco Deep Ocean Disposal Site (55 miles west of Golden Gate)

Review of Dredging Episodes

10. The Water Board participates in the Dredged Material Management Office (DMMO); a working group with representatives of the State and federal agencies with regulatory authority over Bay Area dredging projects. Staff representatives of the Water Board, USACE, U.S. EPA, BCDC, and CSLC meet regularly to jointly review dredging projects and make consensus-based recommendations to their respective agencies about the suitability of sediments for proposed placement sites based on sediment testing conducted according to DMMO testing requirements. Material proposed to be dredged and placed at ocean, inland aquatic, or upland/beneficial reuse sites requires sediment characterization to predict the environmental impacts associated with dredging and dredged material placement activities. The objective of the sediment testing requirements is to ensure that disposal of dredged material at designated disposal sites occurs without causing unreasonable degradation to the surrounding environment. Generally, sediments are tested for physical and chemical attributes and/or the potential for biological toxicity.

    Representatives from the California Department of Fish and Wildlife (CDFW), the U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS) also participate in the DMMO in an advisory capacity. Each DMMO agency retains its independent decision-making authority, but the group has significantly reduced project review time by concurrent consideration of projects. USACE handles the logistics for the operation of the DMMO.

    This Order requires that dredging episodes carried out under this Order will be reviewed by the DMMO for a recommendation on the suitability for disposal or beneficial reuse of the dredged material. Each dredging episode must be approved in writing by Water Board staff.

Barring and Knock-down Dredging

11. **Barring as part of a dredging episode:** USACE plans to implement “barring” as a routine part of dredging episodes to smooth out high-spots as needed after dredging has occurred. This method involves using a tug to pull a weighted blade across the channel bottom. As the blade encounters material, it scrapes the material into the adjoining areas with deeper depressions, redistributing the shoaled material within the project area. Barring will be restricted to the channel footprint and the project depth, including the over dredge depth allowance. If barring were not utilized as part of dredging episodes, the vessel operator would likely have to dredge below project depth in certain areas in order to ensure safe navigation, resulting in an increased volume of material dredged and decreasing overall efficiency.

    Knock-down performed in lieu of dredging: Separate from barring, which is implemented at the end of dredging episodes, USACE anticipates performing several “knock-down” events in lieu of conducting full dredging episodes. Knock-downs would use the same equipment and procedures as barring but would apply to isolated shoals or high-spots rather than an entire channel. Knock-downs are most useful when time constraints may not allow for normal dredging or when a shoal threatening navigation covers a small area of a project area that is otherwise at or below its permitted depth. Conducting separate knock-down operations is often more efficient than mobilizing dredging equipment and transporting the material to a disposal site. Knock-down events occurring separately from full dredging episodes, or in combination with a dredging episode occurring in a different location within the same channel, will be subject to the same coordination with the DMMO as full dredging episodes. The volume of material above project design depth to be knocked down under these separate operations is not anticipated to exceed 15,000 cy per year in each deep draft channel. Each knock-down that is a stand-alone event, and not associated with a dredging episode, must be approved by Water Board staff. Depending on the volume of sediment, contaminant concentrations, and other project-specific details, water quality monitoring may be required and will be coordinated during the episode approval process described in Provision 3.

Advance Maintenance Dredging

12. Advance maintenance dredging is utilized in areas where typical shoaling patterns create navigational restrictions on an ongoing basis. Advance maintenance dredging that does not exceed the yearly maximum volume of dredge material shall be allowed and shall be coordinated through the typical DMMO process. Advance maintenance is restricted to areas that exhibit rapid shoaling and the material shall be characterized through the standard DMMO process. If advance maintenance dredging for any channel is expected to exceed the maximum volume shown in Table 1, or reconfiguration of a channel becomes necessary, USACE will notify the Executive Officer pursuant to Provision 2.

Emergency Dredging

13. USACE is required to ensure that all navigation channels are dredged to a safe depth. If an area is found to be an unacceptable hazard to life or navigation, or threatens to cause an immediate and unforeseen significant economic hardship if corrective action is not taken quickly, USACE may carry out dredging on a limited basis even though that project is not scheduled for dredging. In such cases, an expedited testing and approval process is often necessary. USACE does not anticipate performing more than three emergency dredging episodes consisting of less than 30,000 cy each per year. The Water Board recognizes the need for expedited review of emergency dredging episodes and expects that USACE will still follow the procedures outlined in Provision 3 of this Order for written approval of emergency dredging episodes.

    In atypical conditions, such as after an extraordinary storm event, a shoaling situation may be such an immediate hazard that even an expedited review process is not feasible. The Water Board recognizes that USACE has the authority to remove the immediate hazard without the Executive Officer's approval pursuant to this Order.

Management of the in-Bay Disposal Sites

14. The in-Bay disposal sites are operated as "dispersive" sites, that is, material disposed of at the sites should be dispersed by currents and tidal flows, and the sites should not accumulate material. USACE is responsible for managing and monitoring the sites. USACE manages the total volume, timing, and locations of disposal at the sites and performs regular bathymetric surveys at the sites to determine whether dredged material is accumulating.

15. In the late 1980s, Corps surveys of the Alcatraz disposal site showed a drastic decline in depth and unexpected bottom topography ("mounding"). USACE changed management practices at the Alcatraz site, directing disposal episodes to specific areas within the disposal site, and reducing the monthly allowable volume of disposal during winter months (Corps Public Notice No. 93-3). Table 2, below, shows the monthly and annual

maximum volume targets for all dredgers currently in effect for the in-Bay disposal sites. This Order requires that USACE continue to enforce these maximum disposal volume targets in order to minimize water quality impacts associated with in-Bay disposal of dredged material.

Table 2. Monthly and Annual Maximum Volume Targets

Designated Disposal Site	Monthly Target Volume (cy)	Annual Target Volume (cy)
Alcatraz Island (SF-11)		
October – April	400,000	NA
May – September	300,000	NA
Carquinez Strait (SF-9) – Any Month	1,000,000	NA
San Pablo Bay (SF-10) – Any Month	500,000	NA
Suisun Bay (SF-16)		200,000
Three-year average of the total in-Bay Disposal Volume		1.25 million[a]

a. This volume does not include an allowable contingency volume of 250,000 cy per year but does include the 250,000 cy small dredger allowance

Impacts of Dredging and in-Bay Disposal

16. **Consultations and Work Windows for Dredging:** During the preparation of the 1998 LTMS EIS/EIR, the LTMS agencies initiated State and federal endangered species act (ESA) consultations with CDFW, NMFS, and USFWS for maintenance dredging and disposal projects, covering threatened and endangered species and species of special concern such as the Pacific herring. These programmatic consultations reduced the need for consultation on each individual dredging project by establishing programmatic work windows. These programmatic work windows are based on presence/absence information for various sensitive species and establish times and locations where dredging and disposal activities may take place without further consultation.

In the event that a project cannot be completed during the work window, USACE must consult with the appropriate federal resource agencies. The outcome of the individual consultation determines whether any additional dredging period for that project is appropriate and, if necessary, provides a “take authorization.”

The programmatic consultations resulted in biological opinions issued by NMFS and USFWS that provide federal endangered or threatened species “incidental take” authorization for projects operating in the environmental work window for their area. This “take authorization” protects the dredger from enforcement action in the event of accidental harm to a listed species as a result of the dredging project. The programmatic biological opinions issued by NMFS and USFWS do not address incidental take of State-listed species. Coordination with CDFW is necessary if take of State-listed species is expected. As a federal agency, USACE is not required to obtain authorization from CDFW for incidental take of State-listed species because there has been no waiver of federal sovereignty with respect to the California Endangered Species Act (CESA). The

Water Board, however, as explained further in Finding 18, must comply with CESA when issuing WDRs and Certification.

Since 2011, USFWS has required USACE to consult annually on impacts to delta smelt during dredging of Suisun Bay Channel and New York Slough because of documented occurrences of entrainment during monitoring of hopper dredge use in 2011. USACE will continue to complete annual consultations for hopper dredging of Suisun Bay Channel and New York Slough, as required by USFWS.

USACE and U.S. EPA have reinitiated formal federal Endangered Species Act consultation with NMFS to update its programmatic LTMS biological opinion to include green sturgeon, which was listed as threatened under the federal ESA in 2006. As stated in the October 14, 2014, Corps/U.S. EPA letter documenting agreement with NMFS' Santa Rosa office staff on the updated LTMS program project description, the updated biological opinion will expand the salmonid work window to year-round if dredging is conducted with a clamshell dredge and dredged material is placed at a beneficial reuse site that NMFS agrees will provide aquatic habitat benefits for salmonids, such as a tidal wetlands restoration. Under the updated biological opinion, USACE may opt to dredge certain federal navigation channels with a clamshell dredge outside the work windows and place sediment at a beneficial reuse site without additional consultation with NMFS. All other dredging outside the work window (i.e., hydraulic dredging or clamshell dredging with placement at a non-beneficial reuse site) would require consultation with NMFS and, if applicable, the other resource agencies.

This Order requires that USACE comply with the programmatic LTMS work windows established through consultation with CDFW, NMFS, and USFWS, or initiate individual project consultation and obtain written authorization from the resource agencies for work proposed outside of these windows.

17. **Entrainment of Special-Status including Longfin Smelt and Delta Smelt:** All forms of dredging have the potential to incidentally remove organisms from the environment with the dredged material, a process referred to as entrainment. Organisms on the dredged material may be entrained in addition to organisms in the water column near the dredging apparatus. In general, smaller organisms with limited or no swimming capabilities are more susceptible to entrainment. Mechanical dredging is generally accepted to entrain far fewer fish than hydraulic dredging, because much less water is removed along with the sediment; it still may remove demersal fish and crustaceans that live in or on the sediment. Entrained fish are likely to suffer mechanical injury or suffocation during dredging, resulting in mortality. Longfin smelt and delta smelt are not strong swimmers and are presumed susceptible to entrainment in the flow fields created around the intakes of hydraulic suction dredges. Longfin smelt have the potential to occur in any of the project areas in any season. Delta smelt have potential to occur in the portions of the Estuary that include the Napa River Channel, San Pablo Bay/Mare Island Strait, and Suisun Bay Channel dredge areas during certain seasons. Delta smelt occur in San Pablo Bay in lower numbers than in the Napa River or Suisun Bay; however, they may be present in San Pablo Bay in increased numbers during high water outflow years. Delta smelt are not expected to occur in the other federal channels.

Entrainment Study: Over the past decade, according to CDFW survey data, abundance indices for various life stages of delta smelt have hit record lows, indicating that the species is in imminent danger of extinction. In response, the State elevated its listing status from threatened to endangered in 2010. USFWS listed delta smelt as threatened on March 5, 1993, and designated critical habitat for this species on December 19, 1994. On April 7, 2010, USFWS submitted a 12-month petition finding to reclassify delta smelt as endangered. They found that reclassification is warranted but precluded by other higher-priority listing actions. Similarly for longfin smelt, CDFW annual abundance indices from the fall mid-water trawl surveys show that the population has declined 99 percent or more in the last 45 years, with record lows in the past decade. On March 9, 2009, the State Fish and Game Commission listed longfin smelt as threatened under CESA. On April 2, 2012, USFWS released a 12-month review of longfin smelt status in which it concluded that the listing of the longfin smelt as a threatened species is warranted but is currently precluded by other higher-priority listing actions. As a result, longfin smelt is currently a candidate species for listing under the federal ESA.

In 2013, the United States Army Engineer Research and Development Center (ERDC) prepared a modeling study of entrainment of longfin and delta smelt in San Francisco Bay by hydraulic dredges. In the study, the risk of smelt entrainment was assessed by comparing fish abundances in the environment (CDFW monthly trawls described above) to fish collections in entrainment monitoring samples (screened sub-samples of dredged material) collected during dredging by the hopper dredge *Essayons* in San Francisco Bay in 2010 and 2011. Due to the technical and logistical limitations of sampling on board the working vessel, only a very small fraction, less than one percent of the total volume dredged, was actually sampled.

Modeled estimates of longfin smelt entrainment during hydraulic dredging in 2011 based on 2011 abundance indices are 3,848 for the low entrainment scenario, 6,528 for the medium entrainment scenario, and 10,260 for the high entrainment scenario (up to approximately 8 percent of the median annual population abundance). Modeled estimates of delta smelt entrainment during hydraulic dredging in 2011 based on 2011 abundance indices are 394 for the low entrainment scenario, 1,444 for the medium entrainment scenario, and 3,694 for the high entrainment scenario (up to approximately 29 percent of the median annual population abundance). Many factors are associated with the accuracy of these projections. The small sample size of entrained fish (18 longfin smelt and 4 delta smelt), combined with the low percentage of dredged material sampled, result in a high degree of uncertainty as to the accuracy of the entrainment estimates.

18. **Compliance with CESA:** As a federal agency, USACE is not required to obtain authorization from CDFW for incidental take of State-listed species because there has been no waiver of federal sovereignty with respect to CESA. The Water Board, however, must comply with CESA when issuing WDRs and Certification. In a letter to CDFW dated February 13, 2014, the Water Board requested guidance on the significance of entrainment impacts to special status fish species and on appropriate mitigation measures. In its March 14, 2014, reply to the Water Board (attached), CDFW indicated that impacts would be significant. It noted the ERDC estimates of entrainment and stated that “the Project, as proposed, would substantially reduce the number of an endangered, rare, or threatened species.” To reduce dredging-related impacts to special status fish species to a less-than-significant level, CDFW

recommended reducing hopper dredging to a minimum in San Francisco Bay and implementing the avoidance, minimization, and mitigation measures listed below.

Fish & Game Code section 2053 states "the policy of the State that State agencies should not approve projects … which would jeopardize the continued existence of any endangered species … if there are reasonable and prudent alternatives available consistent with conserving the species.” This Order includes the measures identified by CDFW to avoid, minimize, and mitigate for entrainment impacts, consistent with conserving the species.

Avoidance, Minimization, and Mitigation Measures for Entrainment Impacts: Based on the ERDC entrainment study and guidance from CDFW, the Water Board has determined that implementation of the following measures combined with minimization of hopper dredge use in San Francisco Bay and compensatory mitigation, as required under Provisions 10 and 11, will mitigate potential entrainment impacts to a less-than-significant level:

a. No dredging would occur in water ranging from 0 to 5 parts per thousand salinity between December 1 and June 30.

b. USACE will coordinate with the appropriate regulatory and resource agencies to perform compensatory mitigation for hydraulic dredging anywhere when water temperature is below 22.0ºC.

c. Implementation of a worker education program for listed fish species that could be adversely impacted by dredging. The program would include a presentation to all workers on biology, general behavior, distribution and habitat needs, sensitivity to human activities, legal protection status, and project-specific protective measures.

d. At the beginning and end of each hopper load, pump priming, drag head clearing, and suction of water would be conducted within three feet of the seafloor.

e. Hopper drag head suction pumps would be turned off when raising and lowering the drag arms from the seafloor.

f. Completion of hydraulic hopper dredging in Suisun Bay between August 1 and September 30 to avoid impacts to spawning adult longfin and delta smelt.

g. Completion of hydraulic hopper dredging in Central Bay (i.e., Richmond Outer Harbor) between August 1 and November 30 to avoid impacts to young-of-the-year and spawning adult longfin smelt.

h. Maintaining contact of drag head, cutterheads, and pipeline intakes with the seafloor during suction dredging.

i. Keeping the drag head water intake doors closed to the maximum extent feasible in locations most vulnerable to entraining smelt. In circumstances when the doors need to be opened to alleviate clogging, the doors would be opened incrementally (i.e., the doors would be opened in small increments and tested to see if the clog is removed) to ensure that doors are not fully opened unnecessarily.

19. The Water Board has implemented the San Francisco Estuary Regional Monitoring Program for Trace Substances (RMP) since 1992. The RMP is a coordinated and comprehensive long-term monitoring program with the goal of monitoring water and sediment quality to provide the scientific foundation for managing and improving the

health of the San Francisco Bay aquatic ecosystem. Additionally, the RMP provides for special and pilot studies of interest to program participants. USACE is a participant in the RMP and contributes to the program by funding the United States Geological Survey (USGS) to monitor suspended sediments at an array of locations in the Bay. This monitoring has and will continue to improve understanding of sediment transport processes and create a comprehensive database for various numerical modeling efforts.

CEQA

20. **California Environmental Quality Act (CEQA):** On December 5, 2014, the Water Board issued a draft Environmental Impact Report (EIR) for public review and filed a Notice of Completion with the State Clearinghouse (SCH). (Cal. Code Regs., tit. 14, § 15085.) The public comment period for the draft EIR (SCH No. 2013022056) was from December 5, 2014, to January 20, 2015. The Water Board received and evaluated comments on the draft EIR from public agencies and the other interested parties. Responses to comments received during the comment period have been provided. The Water Board has considered, certified, and approved the final EIR (FEIR) pursuant to California Code of Regulations (CCR), title 14, sections 15090 - 15092.

    The FEIR considers four alternatives:

    - No Project Alternative - Section 15126.6(e)(3)(A) of the CEQA Guidelines states that "when the project is the revision of an existing land use or regulatory plan, policy or ongoing operation, the no project alternative will be the continuation of the existing plan, policy or operation into the future." Therefore, under the No Project Alternative, USACE would continue current maintenance dredging practices for the projects it maintains in the Bay, which include hydraulic suction hopper dredging in three channels inside the Bay (Suisun Bay/New York Slough, Pinole Shoal, and Richmond Outer Harbor) with implementation of all but four of the avoidance, minimization, and mitigation measures for entrainment impacts to longfin smelt and delta smelt listed in Finding 18 and Provision 12.
    - Proposed Project Alternative - Dredging and placement would be conducted as under the No Project Alternative. Also, USACE would implement four additional avoidance, minimization, and mitigation measures for entrainment impacts to longfin smelt and delta smelt (measures f, g, h, and i in Finding 18 and Provision 12) and purchase 0.92 acre mitigation credit at the Liberty Island Conservation Bank, or other approved site, annually for potential impacts to listed species. Provision 12 includes the details on calculation of this mitigation credit.
    - Reduced Hopper Dredge Use Alternative 1 (MSC and One In-Bay Channel) The government hopper dredge *Essayons*, or similarly-sized hopper dredge, would only be used to dredge the MSC and a maximum of one in-Bay federal channel, either the Richmond Outer Harbor or the Pinole Shoal Channel, annually. The channel not selected as the additional hopper dredge channel (i.e., either Pinole Shoal or Richmond Outer Harbor) would be dredged with a mechanical dredge. Suisun Bay/New York Slough Channel would be dredged with a mechanical dredge under this alternative, instead of a hopper dredge. USACE would purchase mitigation credit for entrainment impacts to listed smelt species during hopper dredging in Pinole Shoal or Richmond Harbor as described in the Proposed Project Alternative.

- Reduced Hopper Dredge Use Alternative 2 (MSC only, No In-Bay channels) The government hopper dredge *Essayons*, or similarly-sized hopper dredge, would be used to dredge the MSC. Pinole Shoal, Richmond Outer Harbor, and Suisun Bay/New York Slough Channel would be dredged with a mechanical dredge under this alternative, instead of a hopper dredge. All other dredging, placement activities would be as described for the Proposed Action/Project.

Public Resources Code section 21002 declares the policy of the State that "agencies should not approve projects as proposed if there are feasible alternatives or feasible mitigation measures available which would substantially lessen the significant environmental effects of such projects." (See also, Cal. Code Regs., tit. 14, §§ 15041 ["A lead agency for a project has authority to require feasible changes in any or all activities involved in the project in order to substantially lessen or avoid significant effects on the environment"] and 15042 ["A public agency may disapprove a project if necessary in order to avoid one or more significant effects on the environment would occur if the project were approved as proposed"].) Information in the record to date indicates that both Alternative 1 and Alternative 2 will substantially lessen the significant environmental effects of the Proposed Project. The FEIR concludes that both of these alternatives will reduce the impacts to less than significant. This is also consistent with CDFW's March 14, 2014, memorandum to the Water Board stating that impacts could be made less than significant by reducing hopper dredging to a minimum, implementing the other avoidance, minimization, and mitigation measures identified in Finding 18 and Provision 12, and implementing the compensatory mitigation approach described above. There is no information in the record to date that indicates either Alternative 1 or Alternative 2 is infeasible. For this reason, this Order permits either Alternative 1 or 2.

This Order will not have a significant impact on the environment except as specified below. For the following impacts, this Order has eliminated or substantially lessened all significant effects on the environment where feasible. Pursuant to CCR, title 14, sections 15091 and 15093, the Water Board makes the following CEQA Findings and Statement of Overriding Considerations in conjunction with the approval of this Order:

CEQA Findings

Impact 3.6-4: Potential Adverse Effects from Entrainment on Special-Status or Commercially and Recreationally Important Marine Species, Not Including Delta Smelt and Longfin Smelt

During all forms of dredging, organisms on the dredged material may be entrained in addition to organisms in the water column near the dredging apparatus.

Findings: With implementation of the LTMS work windows as required by Provision 13 and other avoidance, minimization, and mitigation measures intended to reduce the potential for entrainment required by Provision 12, effects to special-status and commercially important species, not including delta smelt and longfin smelt, would not be significant.

Impact 3.6-5: Potential Substantial Adverse Effects and Cumulative Impacts to Delta Smelt from Entrainment

Delta smelt are not strong swimmers and are presumed susceptible to entrainment in the flow fields created around the intakes of hydraulic suction dredges. Delta smelt have potential to occur in the portions of the Estuary that include the Napa River Channel, San Pablo Bay/Mare Island Strait, and Suisun Bay Channel dredge areas during certain seasons.

Findings: Changes or alterations have been required in, or incorporated into, this Order that avoid or substantially lessen the significant environmental effect as identified in the FEIR.

Facts Supporting the Findings:

- This Order requires implementation of reduced hopper dredge use inside San Francisco Bay starting in 2017. At a maximum, a hopper dredge would be used to maintain one federal channel inside the Bay and possibly urgent action removal of a hazardous shoal at Bulls Head Reach in the eastern approach to the Benicia-Martinez Bridge in Suisun Bay Channel if a mechanical dredge is not available (Provision 10).
- This Order requires compensatory mitigation for delta smelt entrainment in the form of mitigation credit purchase at a resource agency-approved habitat conservation bank. The amount of mitigation credit is calculated from an equation (3.0 million acre-feet/800 acres = volume dredged/X acres of mitigation habitat) that was developed by resource agencies to determine mitigation requirements for other projects with entrainment impacts as a result of pumping water (Provision 11).
- This Order requires implementation of specific avoidance, minimization, and mitigation measures, which combined with minimization of hopper dredge use, mitigates potential entrainment impacts to a less-than-significant level (Provision 12).

Impact 3.6-6: Potential Substantial Adverse Effects and Cumulative Impacts to Longfin Smelt from Entrainment

Longfin smelt are not strong swimmers and are presumed susceptible to entrainment in the flow fields created around the intakes of hydraulic suction dredges. Longfin smelt have the potential to occur in any of the project areas in any season.

Findings: Changes or alterations have been required in, or incorporated into, this Order that avoid or substantially lessen the significant environmental effect as identified in the FEIR.

Facts Supporting the Findings:

- This Order requires implementation of reduced hopper dredge use inside San Francisco Bay starting in 2017. At a maximum, a hopper dredge would be used to maintain one federal channel inside the Bay and possibly urgent action removal of a hazardous shoal at Bulls Head Reach in the eastern approach to the Benicia-Martinez Bridge in Suisun Bay Channel if a mechanical dredge is not available (Provision 10).
- This Order requires compensatory mitigation for longfin smelt entrainment in the form of mitigation credit purchase at a resource agency-approved habitat conservation bank. The amount of mitigation credit is calculated from an equation (3.0 million acre-feet/800 acres = volume dredged/X acres of mitigation habitat) that was

developed by resource agencies to determine mitigation requirements for other projects with entrainment impacts as a result of pumping water (Provision 11).

- This Order requires implementation of specific avoidance, minimization, and mitigation measures, which combined with minimization of hopper dredge use, mitigates potential entrainment impacts to a less-than-significant level (Provision 12).

Impacts 3.7-1, 3.7-2, and 3.7-3: Disturbance of Archaeological Resources, Human Remains, and Paleontological Resources

Although unlikely, given the repeated dredging and dredged material placement activities that have historically occurred at the federal navigation channels and existing placement sites, there remains the potential that archaeological materials, human remains, or paleontological materials could be inadvertently uncovered by project activities.

Findings: With implementation of the mitigation measures required by Provision 22, impacts to cultural and paleontological resources would be less than significant. These measures consist of immediate suspension of dredging upon discovery of a resource and consultation with a qualified expert for the particular resource discovered (e.g., archaeologist, paleontologist, local coroner, Native American Heritage Commission).

Statement of Overriding Considerations
The Water Board recognizes that prior to implementation of reduced hopper dredge use in 2017, the project could have significant, unavoidable impacts to biological resources as identified in the FEIR. The Water Board has considered and balanced the economic, legal, social, technological, and other benefits of this Order. The Water Board finds that the unavoidable adverse impacts are acceptable due to overriding concerns. Specifically, the following benefits outweigh the adverse impacts:

- The San Francisco Bay/Delta Estuary is one of the critical maritime thoroughfares in the nation, supporting international trade, commercial and recreational fishing, and recreation. Maintenance dredging is necessary to provide a safe, reliable, and efficient waterborne transportation system (federal channels, harbors, and waterways) for the movement of commerce, national security, and recreation.
- Maintaining the federal channels to their regulatory depths is critical to the region's maritime trade and to the regional and national economies.

In accordance with Title 14 of CCR section 15094, the Water Board will file a Notice of Determination with the State Clearinghouse within five working days from the issuance of the Order.

Basin Plan

21. **San Francisco Bay Basin Water Quality Control Plan (Basin Plan)**
California Water Code section 13240 authorizes the Water Board to develop a Water Quality Control Plan for the San Francisco Bay Basin, which is the Water Board's master water quality control planning document (the Basin Plan). The Basin Plan designates beneficial uses and water quality objectives for waters of the State, including surface waters and groundwater. It also includes implementation programs and policies to achieve those objectives for all waters addressed through the plan. The Basin Plan was duly adopted by the Water Board and approved by the State Water Board, U.S. EPA, and

the Office of Administrative Law where required. The latest version can be found on the Water Board's website at http://www.waterboards.ca.gov/sanfranciscobay/basin_planning.shtml. Requirements in this Order implement the Basin Plan.

The existing beneficial uses of San Francisco Bay in the vicinity of the dredging and disposal areas are:

- Industrial service supply (IND)
- Industrial process supply (PROC)
- Commercial and sport fishing (COMM)
- Shellfish harvesting (SHELL) (Central Bay only)
- Estuarine Habitat (EST)
- Fish migration (MIGR)
- Preservation of rare and endangered species (RARE)
- Fish Spawning (SPWN)
- Wildlife habitat (WILD)
- Water contact recreation (REC-1)
- Noncontact water recreation (REC-2)
- Navigation (NAV)

Notification

22. USACE and interested persons have been notified of the Water Board's intent to issue requirements for USACE and have been provided with the opportunity to submit their written comments.

The Water Board, in a properly noticed public hearing on May 13, 2015, heard and considered all comments pertaining to the project.

IT IS HEREBY ORDERED, pursuant to the provisions of Division 7 of the California Water Code and regulations adopted thereunder and other State regulations, as applicable, and to the provisions of the federal Clean Water Act, as amended, and regulations and guidelines adopted thereunder, that USACE shall comply with the following:

A. RECEIVING WATER LIMITATIONS

1. The dredging and disposal activities shall not create a nuisance as defined in section 13050(m) of the California Water Code.

2. The discharge of waste shall not cause the following conditions to exist in waters of the State that cause a nuisance or adversely affect beneficial uses at any place:

   a. Floating, suspended, or deposited macroscopic particulate matter or foam;

   b. Aquatic growths;

   c. Significant alteration of temperature, turbidity, or apparent color beyond present natural background levels;

   d. Visible, floating, suspended, or deposited oil or other products of petroleum origin; and

e. Toxic or other deleterious substances in concentrations or quantities which will cause deleterious effects on aquatic biota, wildlife, or waterfowl, or which render any of these unfit for human consumption either at levels created in the receiving waters or as a result of biological concentration.

3. The discharge of waste shall not cause violations of the following limits in the water column at dredging and disposal sites:

a. Dissolved Oxygen:	5.0 mg/l minimum downstream of the Carquinez Bridge, 7.0 mg/l minimum upstream of the Carquinez Bridge. When natural factors cause lesser concentrations, then this discharge shall not cause further reduction in the concentration of dissolved oxygen.
b. Dissolved Sulfide:	0.1 mg/l maximum.
c. pH:	A variation of natural ambient pH by more than 0.5 pH units.
d. Un-ionized Ammonia:	0.025 mg/L as N, annual median; and 0.16 mg/L as N, maximum.
e. Salinity:	The project shall not increase total dissolved solids or salinity to adversely affect beneficial uses

4. The discharge shall not cause a violation of any applicable water quality objectives for receiving waters adopted by the Water Board and the State Water Board as required by the Clean Water Act and regulations adopted thereunder. If more stringent applicable water quality standards are promulgated or approved pursuant to section 303 of the Clean Water Act, or amendments thereto, the Water Board will revise and modify this Order in accordance with such more stringent standards.

B. PROVISIONS

Project and Project Changes

1. This Order authorizes:

- San Francisco Bar Channel - Placement of approximately 2.5 mcy of sand at SF-8, OBDS/SF-17, and, if approved by applicable regulatory and resource agencies, the Ocean Beach onshore placement site.

- San Francisco Bay - Dredging up to 12.4 mcy of sediment (based on maximum dredging volumes in Table 1, assuming that Redwood City Harbor is dredged annually and that the smaller, non-annual projects [Napa River Channel, Petaluma River Channel, San Rafael Creek Channel, and San Leandro Marina Channel] are dredged once each during 2015-2019) with disposal of a maximum of 3.5 mcy at the in-Bay disposal sites. Placement of dredged material at beneficial reuse locations within the Water Board's jurisdiction is regulated through site-specific Water Board orders for each location. Disposal of dredged material may also occur at the Deep Ocean Disposal Site, SF-DODS, beyond the jurisdiction of the Water Board.

2. The District Engineer shall inform the Executive Officer in writing of any changes to the project plan in Table 1 of this Order. The Executive Officer shall determine whether such a proposed change requires modification of the WDRs and Certification issued herein, in which case the District Engineer shall submit a request for revised WDRs and Certification for action by the Board. Proposed changes that would require modification to this Order include but are not limited to any changes that may result in an overall increase in the amount of in-Bay disposal or an increased threat to water quality. The Executive Officer may approve minor project changes that do not require modification to this Order and which will not result in an increased threat to water quality.

Episode Approval

3. Individual dredging and disposal episodes, including knock-down events, shall not commence until authorized in writing by Water Board staff following review by the DMMO. USACE shall provide an episodic approval package to Water Board staff for each proposed project. This package shall name the proposed disposal or beneficial reuse location and verify that placement of dredged material there is in line with USACE's current evaluation of alternative disposal sites described in Provision 9. The package shall also contain the current condition survey, the estimated volume to be dredged based on that survey, and either a Tier I Evaluation or the sampling and analysis data report. The estimated volume will include the two feet of allowable over depth, and this will be identified separately from the volume of material above project depth. This episodic approval package shall request concurrence pursuant to a favorable suitability determination from the DMMO agencies.

   Episode Approval Package Due Date: A minimum of 30 days prior to anticipated dredging start date.

4. USACE conducts a pre-dredge (in USACE terminology, before-dredge, or "BD") survey within 30 days to two weeks before the dredge start date. The estimated volumes based on the BD survey shall be evaluated against the volumes estimated from the condition survey. If there is a 15 percent or greater increase in the dredge volumes, USACE shall notify Water Board staff immediately. This notification shall include the new estimated volume and USACE's proposal for placement of that material. USACE shall notify Water Board staff of any changes in material placement location, regardless of any volume changes.

Dredging and Disposal Operations

5. Dredging at each project location shall be limited to the project depths shown in Table 1 with no more than two feet of over-dredge allowance.

6. **Overflow/Decanting During Mechanical Dredging:** No water entrained during dredging (i.e., overflow or decant water) shall be discharged from any vessel containing dredged material characterized as containing greater than 20 percent fines (silt- and clay-size particles), with the exception of spillage incidental to clamshell bucket operations. Decanting is allowed when the fine-grain content of the dredged material is less than 20 percent (i.e., the sediment is greater than 80 percent sand).

   Exceptions may be granted on a project-specific basis if USACE submits an overflow or decanting monitoring plan, acceptable to the Executive Officer, at least 90 days prior to the anticipated dredging start date. The plan shall describe the process for monitoring compliance with the following receiving water limits within 500 feet of the dredge footprint (a shorter distance may apply in Richmond and Oakland Inner Harbors depending on the distance to the nearest eelgrass bed or patch):

- Turbidity ≤ 50 NTU (or up to 10 percent greater than turbidity at a background reference location sampled concurrently with the dredging location, if the background turbidity is greater than 50 NTU)
- Dissolved oxygen ≥ 5.0 mg/L (≥ 7.0 mg/L east of the Carquinez Bridge)
- 6.5 ≤ pH ≤ 8.5

In addition, the monitoring plan shall: 1) describe how the temporal and spatial extent of the suspended sediment plume associated with overflow/decant discharge will be characterized and compared to non-overflow conditions; 2) describe reporting format and frequency; and 3) include a contingency plan in the event of an observed exceedance of one or more water quality objectives caused by overflow/decant discharges.

Project-Specific Overflow Monitoring Plan Due Date: A minimum of 90 days prior to anticipated dredging start date. Dredging may not commence until the plan is approved in writing by Water Board staff.

7. Return water overflow from hopper-type suction dredges shall be limited to no longer than 15 minutes at the dredge site for each hopper load except in channels where the shoaled material contains greater than 80 percent sand. There is no overflow restriction if the dredged material is greater than 80 percent sand.

8. During transportation from the dredging site to the placement site, no dredged material shall be permitted to overflow, leak, or spill from barges, bins or dump scows.

Alternatives Analysis

9. USACE shall, as part of the episode approval process, submit to the Water Board an evaluation of alternative disposal sites pursuant to section 404(b)(1) of the Clean Water Act. This type of evaluation, also known as an “Integrated Alternatives Analysis,” or IAA, shall incorporate all Corps dredging projects (annual and non-annual) over as many years/dredging cycles as possible, up to a maximum of five years, and shall evaluate the practicability of the following beneficial reuse and disposal options:

   - Habitat Restoration: USACE shall evaluate the feasibility of placing dredged material at habitat restoration sites within the San Francisco Bay Region and take dredged material to those sites where it is feasible. USACE shall make good faith efforts to coordinate with habitat restoration projects that are seeking dredged material.
   - Levee Restoration: USACE shall evaluate the feasibility of placing the dredged material in question at levee restoration sites within the San Francisco Bay Region and take dredged material to those sites where it is feasible. USACE shall make good faith efforts to coordinate with levee restoration projects that are seeking dredged material.
   - Beneficial Reuse and Rehandling Sites: USACE shall evaluate the feasibility of placing the dredged material in question at beneficial reuse sites and dredged material

rehandling sites within the San Francisco Bay Region and take dredged material to those sites where it is feasible.

- Coordination with other Corps Projects: USACE shall evaluate the feasibility of combining placement of dredged material with that from other Corps projects implementing beneficial reuse when both projects will occur at similar times or locations or will be performed by the same contractor.

Protection of Special Status Species

10. **Phased-In Reduction of Hydraulic Suction Hopper Dredging Inside San Francisco Bay:** According to CDFW, minimization of hopper dredging inside San Francisco Bay, combined with the measures described in Provision 12, is necessary to mitigate potential entrainment impacts to longfin and delta smelt to a less-than-significant level. Currently, USACE proposes to continue using a government hopper dredge in Richmond Outer Harbor, Suisun Bay and New York Slough, and Pinole Shoal. Due to USACE's three-year budget process for its operations and maintenance program, the earliest that the San Francisco District could obtain additional funding to transition from hopper dredging to mechanical dredging in the three channels listed above would be federal fiscal year 2017 (FY 2017), October 1, 2017, through September 30, 2018. Therefore, starting in FY 2017, USACE shall significantly reduce hydraulic dredging inside San Francisco Bay by the government hopper dredge *Essayons*, or similarly sized hopper dredge, by implementing one of the following options on an annual basis:

    - **MSC and One In-Bay Channel:** Limit hopper dredge use to a maximum of one in-Bay federal channel, either the Richmond Outer Harbor or the Pinole Shoal Channel, but not the Suisun Bay Channel. Certain conditions, including rough seas, strong currents, fog, heavy rain, strong winds, heavy vessel traffic, or a combination of these factors may preclude safe dredging with a hopper dredge at the MSC. Dredging an in-Bay channel, whereby the dredge would move into San Francisco Bay and work on the identified channel, then return to the MSC as soon as conditions allow, would maximize efficient use of the hopper dredge.

      The MSC, Pinole Shoal Channel, and Richmond Outer Harbor are not within the typical range of the delta smelt; therefore, the potential adverse effects to delta smelt resulting from dredge entrainment would be largely eliminated under this alternative. Because urgent action dredging of the Bulls Head Reach may occur at any time of year, it is likely that some longfin smelt and delta smelt would be entrained during some dredging episodes if a mechanical dredge is unavailable and a hopper dredge must be used. The potential for entrainment would be reduced with the use of a mechanical dredge. Because the extent and frequency of critical dredging episodes at Bulls Head Reach cannot be predicted, appropriate mitigation for these episodes, if warranted based on expected impacts, would be determined in coordination with regulatory agencies at time they occur.

    - **MSC Only, No In-Bay Channels:** Limit hopper dredge use to the MSC and urgent action removal of any hazardous shoal at Bulls Head Reach in the eastern approach to the Benicia-Martinez Bridge in Suisun Bay Channel if a mechanical dredge is not available. Due to the strong currents and waves in the MSC, a hopper dredge is the only equipment that can safely dredge the channel. Because this option avoids and minimizes entrainment take of longfin and delta smelt to the maximum extent practicable, no compensatory mitigation or further entrainment monitoring is required.

Because urgent action dredging of the Bulls Head Reach may occur at any time of year, it is likely that some longfin smelt and delta smelt would be entrained during some dredging episodes if a mechanical dredge is unavailable and a hopper dredge must be used. The potential for entrainment would be reduced with the use of a mechanical dredge. Because the extent and frequency of critical dredging episodes at Bulls Head Reach cannot be predicted, appropriate mitigation for these episodes, if warranted based on expected impacts, would be determined in coordination with regulatory agencies at time they occur.

11. **Compensatory Mitigation for Implementation of Reduced Hopper Dredging Option 10 a.:** Because reduced hopper dredge use may not be implemented until fiscal year 2017, USACE shall purchase 0.92 acre mitigation credit at Liberty Island Conservation Bank for potential impacts to longfin smelt in fiscal years 2015 and 2016 if a hopper dredge is used in the Suisun Bay and New York Slough, Pinole Shoal, and Richmond Outer Harbor Channels. The 0.92 acre mitigation credit was calculated from an equation (3.0 million acre-feet/800 acres = volume dredged/X acres of mitigation habitat) that was developed by resource agencies to determine mitigation requirements for other projects with entrainment impacts as a result of pumping water, including the State Water Project. For volume dredged, available government-hopper-dredge–pumped total sediment and water volumes for 2006 through 2012 were reviewed. The highest volume for each of the in-Bay channels (Pinole Shoal, Richmond Outer Harbor, and Suisun Bay Channel/New York Slough) from this period was used in the calculation. Of the 0.92 acre mitigation credit, 0.19 acre mitigation credit is for Pinole Shoal, 0.34 acre mitigation credit is for Richmond Outer Harbor, and 0.39 acre mitigation credit is for Suisun Bay Channel and New York Slough.

    Beginning in fiscal year 2017 and each subsequent year, USACE shall purchase no less than 0.19 acre mitigation credit at the Liberty Island Conservation Bank, or other CDFW-approved conservation bank providing habitat benefitting listed smelt species if Pinole Shoal is dredged with a hopper, and no less than 0.34 acre mitigation credit if Richmond Outer Harbor is dredged with a hopper.

12. **Avoidance, Minimization, and Mitigation Measures for Entrainment Impacts:** USACE shall implement the following measures to mitigate potential entrainment impacts to a less-than-significant level:

    a. No dredging would occur in water ranging from 0 to 5 parts per thousand salinity between December 1 and June 30.

    b. USACE will coordinate with the appropriate regulatory and resource agencies to perform compensatory mitigation for hydraulic dredging anywhere when water temperature is below 22.0ºC.

    c. Implement a worker education program for listed fish species that could be adversely impacted by dredging. The program would include a presentation to all workers on biology, general behavior, distribution and habitat needs, sensitivity to human activities, legal protection status, and project-specific protective measures.

d. At the beginning and end of each hopper load, pump priming, drag head clearing, and suction of water would be conducted within three feet of the seafloor.

e. Hopper drag head suction pumps would be turned off when raising and lowering the drag arms from the seafloor.

f. Completing hydraulic hopper dredging in Suisun Bay between August 1 and September 30, to the extent feasible[1], to avoid impacts to spawning adult longfin and delta smelt.

g. Completing hydraulic hopper dredging in Central Bay (i.e., Richmond Outer Harbor) between August 1 and November 30, to the extent feasible[1], to avoid impacts to young-of-the-year and spawning adult longfin smelt.

h. Maintaining contact of drag head, cutterheads, and pipeline intakes with the seafloor during suction dredging.

i. Keeping the drag head water intake doors closed to the maximum extent feasible in locations most vulnerable to entraining smelt. In circumstances when the doors need to be opened to alleviate clogging, the doors would be opened incrementally (i.e., the doors would be opened in small increments and tested to see if the clog is removed) to ensure that doors are not fully opened unnecessarily.

13. **Entrainment Monitoring for Implementation of Reduced Hopper Dredging Option 10 a.:** USACE shall submit an entrainment monitoring plan, acceptable to the Executive Officer, for collecting data to increase the accuracy of existing entrainment rate estimates for delta smelt, longfin smelt, and other special status fish species in hydraulic hopper dredges during maintenance dredging in San Francisco Bay. At a minimum, the plan shall include the following elements:

- On-board monitoring during active dredging.
- Sampling during all phases of the dredging cycle.
- Sampling both drag-arms to capture a greater percentage of the pump volume during active dredging.
- Sampling associated with flood/ebb tides and spring/neap tides.
- Visual monitoring of vessel hold for fish that are not captured by sampling screens during active dredging.
- Presence/absence fish monitoring in the immediate vicinity of the dredge during active dredging to understand if sampling is effective.

The plan shall also describe procedures for evaluating the effectiveness of the measures required by Provision 12 and include a schedule for completing the monitoring and submitting a final report to the Water Board.

Entrainment Monitoring Plan Due Date: July 31, 2015.

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[1] Feasibility is contingent upon the availability of federal funds (e.g., timing of Congressional appropriations) to execute the dredging work, as well as by the availability of dredging equipment to perform the dredging work at the referenced time and locations.

14. Dredging and disposal activities shall be limited to the work windows set out by CDFW, NMFS, and USFWS in their most recent programmatic consultations on the LTMS unless USACE consults individually with the appropriate resource agencies and provides Water Board staff with written authorization from the resource agency or agencies consulted, to work outside these windows.

15. This Order does not allow for the take, or incidental take, of any special status species. USACE is required, as prescribed in the State and federal endangered species acts, to consult with the appropriate agencies prior to commencement of the project. USACE shall use the appropriate protocols, as approved by the CDFW, NMFS, and/or USFWS, to ensure that project activities do not adversely impact preservation of rare and endangered species, a beneficial use of San Francisco Bay and its tributaries as set forth in the Basin Plan.

16. USACE shall comply with the Conservation Measures set forth in the June 9, 2011, Programmatic Essential Fish Habitat (EFH) Consultation Agreement between USACE, U.S. EPA, and NMFS. The Conservation Measures are intended to enhance the environmental protectiveness of the LTMS program for EFH, which the Magnuson-Stevens Fishery Conservation and Management Act defines as "waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity," for all managed fish species.

Management and Monitoring of Dredging and Disposal of Dredged Material

17. USACE shall maintain administrative controls on disposal volumes at the in-Bay disposal sites for all navigation dredging projects under the LTMS so that target volumes in Table 2 of this Order are not exceeded. USACE shall manage overall disposal volumes and disposal locations within each site to prevent build-up of dredged material at the sites.

18. **Post-Dredge Survey:** USACE shall ensure that post-dredge bathymetric surveys for federal dredging projects are conducted within 30 days of completion of dredging in all federal navigation channels, regardless of whether they are dredged by a contractor or by a federal government dredge.

19. **Post-Dredge Report:** USACE shall provide a post-dredge report shall to Water Board staff and the USACE DMMO database manager within 60 days of completion of dredging operations for each federal dredging project. The report shall contain the dates of dredging, maps of the dredging footprint, the calculated final dredging volume, and the placement location or locations and volumes per location if more than one site was used. In addition, for hydraulic dredging projects, the report submitted to Water Board staff shall describe the implementation and effectiveness of all applicable entrainment mitigation measures listed in Provision 12.

20. USACE shall provide a technical report that documents monitoring efforts designed to evaluate the water quality impacts of the dredged material discharge on waters of the State, pursuant to California Water Code (Water Code) section 13267.

    Regional Monitoring Program: Provision 19 is a requirement for a technical report. The Water Board requires dischargers of waste materials to the Bay, including those who dispose of dredged material, to monitor the impacts of their discharges pursuant to Water

Code section 13267. This monitoring provides necessary information about ambient Bay water quality and potential long-term impacts of dredged material disposal.

In previous years, USACE has participated in the San Francisco Estuary Regional Monitoring Program for Trace Substances (RMP) by funding USGS to monitor suspended sediments at an array of locations in the Bay. The RMP is a coordinated and comprehensive long-term monitoring program with the goal of monitoring water and sediment quality to provide the scientific foundation for managing and improving the health of the San Francisco Bay aquatic ecosystem. Suspended sediment monitoring has and will continue to improve understanding of sediment transport processes and create a comprehensive database for various numerical modeling efforts. Implementation or funding of the RMP study program or other Water Board-approved study will constitute fulfillment of this provision.

21. USACE shall continue bathymetric monitoring of the in-Bay disposal sites (monthly surveys at the Alcatraz disposal site, quarterly surveys elsewhere). USACE shall keep a record of these surveys on file and shall make them available for inspection by the Water Board, other regulatory agencies, and interested members of the public upon written request to USACE staff.

Disturbance of Historical or Unique Archaeological Resources, Human Remains, or Significant Paleontological Resources

22. In the unlikely event that any of the resources listed above are discovered during maintenance dredging in the federal channels, USACE will immediately cease dredging, notify Water Board staff, and consult a qualified expert for the particular resource discovered (e.g., archeologist, paleontologist, local coroner, Native American Heritage Commission).

Standard Provisions

23. The discharge of dredged materials to the waters of the State shall cease immediately whenever violations of this Order are detected by USACE or by Water Board staff as determined by the Executive Officer, and the discharge shall not resume until compliance can be assured to the Executive Officer's satisfaction.

24. USACE shall provide the Water Board or its authorized representative, in accordance with Water Code section 13267(c), with the following:

- Entry upon premises in which any required records are kept.
- Access to copy any records required to be kept under terms and conditions of this order.
- Access to inspect monitoring equipment or records.
- Access to sample any discharge.
- Small craft transport to offshore locations or vessels for the purpose of inspection, provided that it is within normal business hours.

25. **Certification**
The Water Board hereby certifies that any discharge from the referenced project will

comply with the applicable provisions of Clean Water Act sections 301 (Effluent Limitations), 302 (Water Quality Related Effluent Limitations), 303 (Water Quality Standards and Implementation Plans), 306 (National Standards of Performance), and 307 (Toxic and Pretreatment Effluent Standards), and with other applicable requirements of State law. Clean Water Act section 401 directs the agency responsible for certification to prescribe effluent limitations and other limitations necessary to ensure compliance with the Clean Water Act and with any other appropriate requirement of State law. Section 401 further provides that State certification conditions shall become conditions of any federal license or permit for the project. The conditions of this Certification must be met to ensure that the project will comply with water quality standards, any applicable effluent limitation, standard of performance, prohibition, effluent standard, or pretreatment standard required pursuant to the Clean Water Act sections listed above and to ensure that the project will comply with any other appropriate requirements.

26. This Order applies to the project as proposed in application materials and conditioned and approved in this Order. Failure to implement the project as proposed is a violation of this Order. Violation or threatened violation of the conditions of this Order is subject to remedies including, but not limited to, penalties or injunctive relief as provided under applicable State or federal law.

27. This Order is subject to modification or revocation upon administrative or judicial review, including review and amendment pursuant to Water Code section 13330 and 23 CCR section 3867. The Water Board may add to or modify the conditions of this Order, as appropriate, to implement any new or revised water quality standards and implementation plans adopted and approve pursuant to the Water Code,or section 303 of the Clean Water Act, or in response to new information concerning the conditions of the project.

28. This Order is not intended and shall not be construed to apply to any discharge from any activity involving a hydroelectric facility requiring a Federal Energy Regulatory Commission (FERC) license or an amendment to a FERC license unless the pertinent certification application was filed pursuant to 23 CCR subsection 3855(b) and that application specifically identified that a FERC license or amendment to a FERC license for a hydroelectric facility was being sought.

29. This Order does not remove liability under federal, State, or local laws, regulations or rules of other programs and agencies, nor does this Order authorize the discharge of wastes without appropriate permits from other agencies or organizations.

30. This Order supersedes Order No. R2-2007-0020. Order No. R2-2007-0020 is hereby rescinded.

I, Bruce H. Wolfe, Executive Officer, do hereby certify the foregoing is a full, true, and correct copy of an Order adopted by the California Regional Water Quality Control Board, San Francisco Bay Region, on May 13, 2015.

BRUCE H. WOLFE
EXECUTIVE OFFICER

ATTACHMENTS:

CDFW Memorandum dated March 14, 2014

Figure 1. Federal Navigation Projects and Dredged Material Placement Sites

Figure 2. San Francisco Main Ship Channel

Figure 3. Oakland Harbor

Figure 4. Richmond Harbor

Figure 5. Suisun Bay Channel and New York Slough

Figure 6. Pinole Shoal

Figure 7. Redwood City Harbor

Figure 8. Napa River Channel

Figure 9. Petaluma River Channel

Figure 10. San Rafael Creek Channel

Figure 11. San Leandro Marina (Jack D. Maltester Channel)

State of California
Department of Fish and Wildlife

Flex your Power

Memorandum

Date: March 14, 2014

To: Bruce H. Wolfe, Executive Officer
Regional Water Quality Control Board
San Francisco Bay Region
1515 Clay Street, Suite 1500
Oakland, CA 94612

From: Craig Shuman, Regional Manager
Marine Region
1933 Cliff Drive, Suite 9
Santa Barbara, CA 93109

Scott Wilson, Regional Manager
Bay Delta Region
7329 Silverado Trail
Napa, CA 94558

Subject: California Department of Fish and Wildlife Response to Request for Guidance on CEQA Issues Related to Take of State-Listed Fish Species under the U.S. Army Corps of Engineers San Francisco Bay Navigational Dredging Program

The California Department of Fish and Wildlife (Department) has reviewed your memorandum dated February 13, 2014 requesting input from the Department regarding the significance of impacts to biological resources and proposed mitigation for the U.S Army Corps of Engineers (USACE) Operation and Maintenance Dredging of Federal Channels in San Francisco Bay for ten years (Project) as it is evaluated in the Administrative Draft Environmental Impact Report (EIR) being prepared by the Regional Water Quality Control Board (RWQCB). In addition, the Department has reviewed portions of the EIR and the USACE Risk Assessment for Hopper Dredging in San Francisco Bay, and has participated in the Interagency Longfin Smelt Working Group since 2010 to assess the impacts of the Project on protected fish species and proposals for minimization and mitigation measures.

Under Fish and Game Code (FGC) section 711.7, the Department is designated as trustee for the State's fish and wildlife resources. The Department has jurisdiction over the conservation, protection, and management of fish, wildlife, native plants, and habitat necessary for biologically sustainable populations of those species (FGC §1802). The Department administers the California Endangered Species Act (CESA) (FGC §2050, et seq.) and other provisions of the FGC that conserve the State's fish and wildlife public trust resources. The Department also serves as a trustee agency in the California Environmental

Quality Act (CEQA) process, as a state agency with jurisdiction over the fish and wildlife resources affected by the Project, specifically Delta smelt, listed as endangered, and longfin smelt, listed as threatened under CESA [14 C.C.R. §§ 670.5(a)(2)(O), (b)(2)(E)]. It is in our role as a trustee that we have participated in the Interagency Longfin Smelt Working Group and are providing our recommendations.

Your memorandum dated February 13, 2014 asked five questions about the significance of impacts from USACE hopper dredging and mitigation and monitoring for those impacts. The Department has prepared the following responses for your consideration:

1. *Consistent with CEQA Guidelines section 15065 (a) (1), Mandatory Findings of Significance, is it CDFW's opinion that ongoing hopper dredging as proposed by the Corps (in light of the administrative record) will substantially reduce the number of an endangered, rare or threatened species (defined in CEQA Guidelines section 15380?*

    - The Department recognizes that the determination of Significance is at the discretion of the Lead Agency.

    - The USACE estimated the range of take from the Project in 2011 as 3,848 to 6,058 longfin smelt and 394 to 2,822 Delta smelt. Entrainment of these fish is "take" as defined in the Fish and Game Code (FGC §86). The Project includes ten years of dredging operations. It is the Department's belief that the Project, as proposed, would substantially reduce the number of an endangered, rare, or threatened species. In addition, the combined cumulative impact associated with this Project and the effects of other projects causing related impacts would be significant.

    - Due to uncertainty in the sampling data to date, it is prudent to take a precautionary approach and assume that the estimates of take are low for State-listed species that are potentially impacted by the dredging activity. In addition, a Significance determination should consider the overall population abundance of these species, which is currently very low compared to historic levels.

2. *If the impact is considered significant because of the substantial reduction in the number of threatened or endangered species, what potentially feasible mitigation does CDFW recommend to avoid or substantially reduce the impact to a less-than-significant level, assuming the worst-case take scenario?*

    - The Department offers the following recommendations to reduce the impacts of USACE dredging on state-listed species.

        - Reduce hopper dredging to a minimum in San Francisco Bay. The Reduced Hopper Dredge Alternative 1 in the Administrative Draft EIR would reduce hopper dredging to only one channel inside the Bay per year. All other navigational channels would be dredged annually using mechanical methods. The Department will review all alternatives that are developed and comprehensively evaluated in the Draft EIR, in order to consider potential impacts to all fish and wildlife resources.

- Dredge in Central Bay later in the year from August 1--November 30 to allow young-of-the-year longfin smelt to grow larger and spawning adults to return upstream.
- Dredge in Suisun Bay earlier during the dredging window from August 1--September 30 to avoid spawning adults.
- Keep water intake ports on drag-heads closed at all times during dredging in San Francisco and Suisun bays.
- Turn off drag-arm pumps when vessel is repositioning, moving to other locations, and drag-heads are off-bottom.
- Follow the minimization measures currently in place for the navigational dredging in San Francisco Bay according the Department's 2011 letter to the USACE.

- The Department has recommended that the USACE mitigate for its take of both longfin and Delta smelt by purchasing appropriate credits from an approved mitigation bank.

- Currently, the USACE has calculated its mitigation for hopper dredging using the State Water Project mitigation equation, using the highest pump volume over the past eight years. This provides a compensatory mitigation of 0.92 acres per year of the Project.

3. *What is CDFW's opinion of the effectiveness of the mitigation proposed by the Corps to avoid or substantially reduce the impact to a less-than-significant level?*

   USACE proposed 0.92 acres of restored and managed tidal wetlands per year as compensatory mitigation to reduce impacts to less-than-significant level. The amount and type of mitigation appropriate to reduce an impact to a less-than-significant level depends on the level of impact. While additional Project monitoring would provide a more accurate level of impact to State-listed fish, the mitigation proposed by USACE is generally consistent with mitigation applied to other projects that cause take of longfin smelt and Delta smelt associated with water diversion or extraction. Therefore, in the Department's opinion, it would not be inappropriate for RWQCB to rely on the identified minimization measures and the identified compensatory mitigation approach to reduce Project impacts to a less-than-significant level.

4. *What monitoring, if any, does CDFW recommend?*

   The Department believes that further monitoring should occur to evaluate the effectiveness of the proposed minimization measures, more specifically quantify the level of take, and determine whether additional minimization measures or mitigation measures are warranted. On-board monitoring has only occurred during two years of dredging (2010 and 2011) and encompassed a very small fraction of the dredge volume both years (<1%). To increase understanding of the impact of dredging on State-listed species and develop adaptive management measures, the Department recommends the following:

   - On board monitoring during active dredging.

- Sampling during all phases of the dredging cycle.
- Sampling both drag-arms to capture a greater percentage of the pump volume during active dredging.
- Sampling associated with flood/ebb tides and spring/neap tides.
- Visual monitoring of vessel hold for fish that are not captured by sampling screens during active dredging.
- Presence/absence fish monitoring in the bay around the dredge during active dredging to understand if sampling is effective.

If implemented, monitoring should be conducted for the two years following Project approval. This data compiled in a final report would provide guidance on future minimization measures related to dredging efforts conducted in the San Francisco Bay and Estuary for both federal, State, and private dredging efforts.

5. *What adaptive management or remedial measures does CDFW recommend in response to monitoring results?*

    - Refinement of current minimization and monitoring measures.
    - If necessary, additional minimization measures such as additional work window restrictions and/or a further reduction in hopper dredge use.

We appreciate the opportunity to assist RWQCB with the assessment of CEQA considerations for this Project. The Department is available to discuss our responses in more detail. If you have any questions, please contact Ms. Becky Ota, Environmental Program Manager-Marine Region, at (650) 631-6789 or Becky.Ota@wildlife.ca.gov; or Mr. Jim Starr, Environmental Program Manager-Bay Delta Region, at (209) 234-3440 or Jim.Starr@wildlife.ca.gov.

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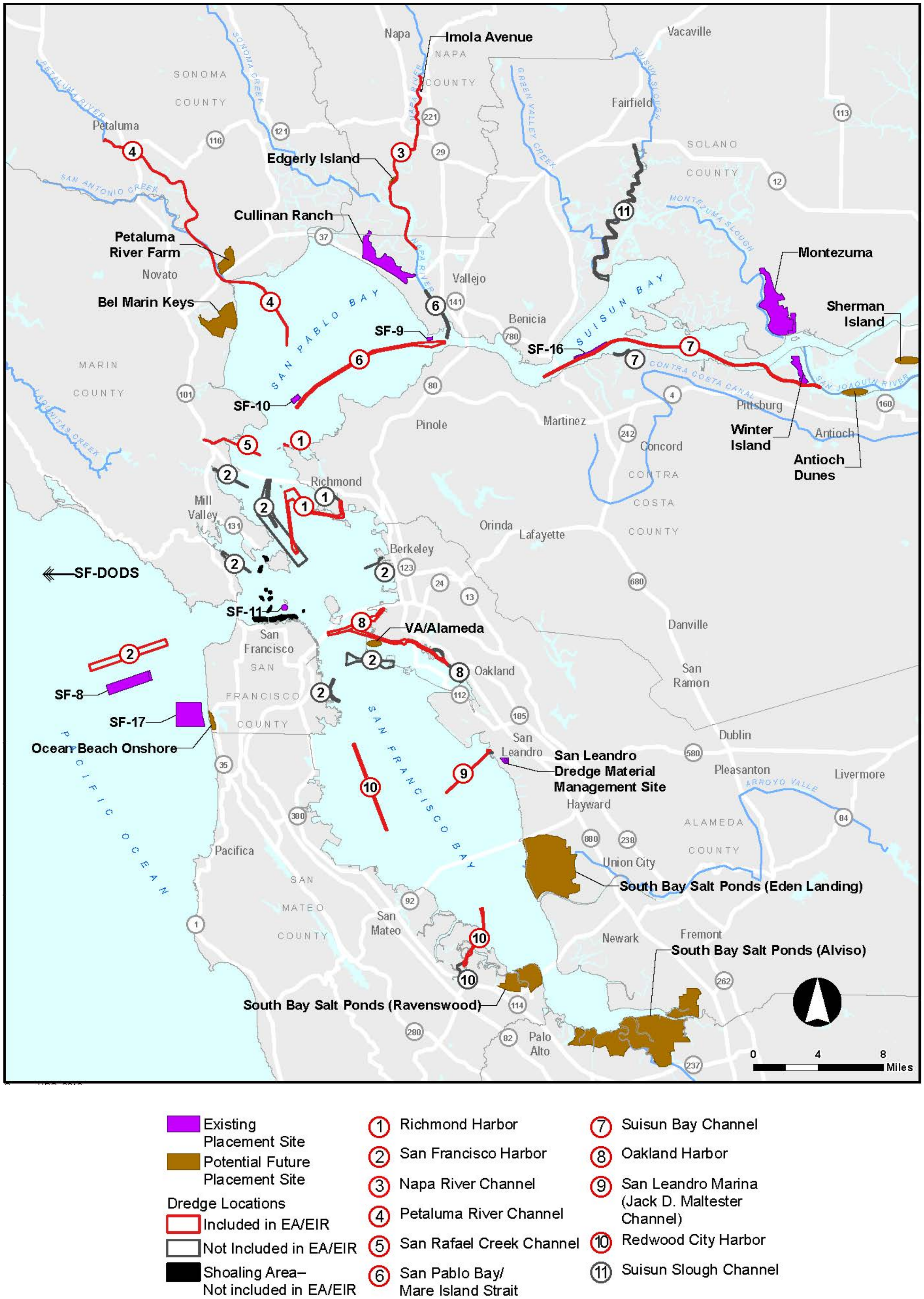

Figure 1. Federal Navigation Projects and Dredged Material Placement Sites

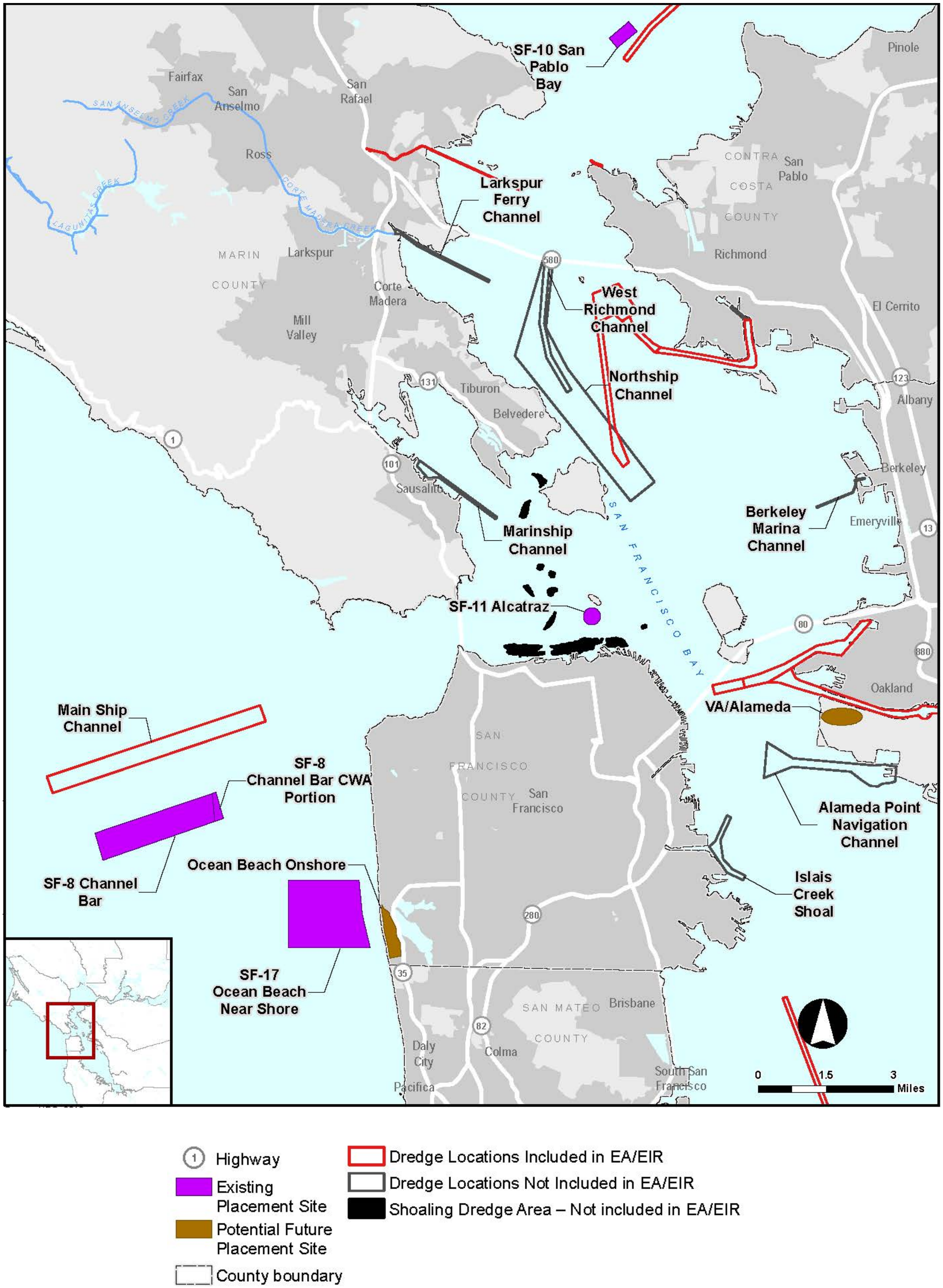

Figure 2. San Francisco Harbor – Main Ship Channel

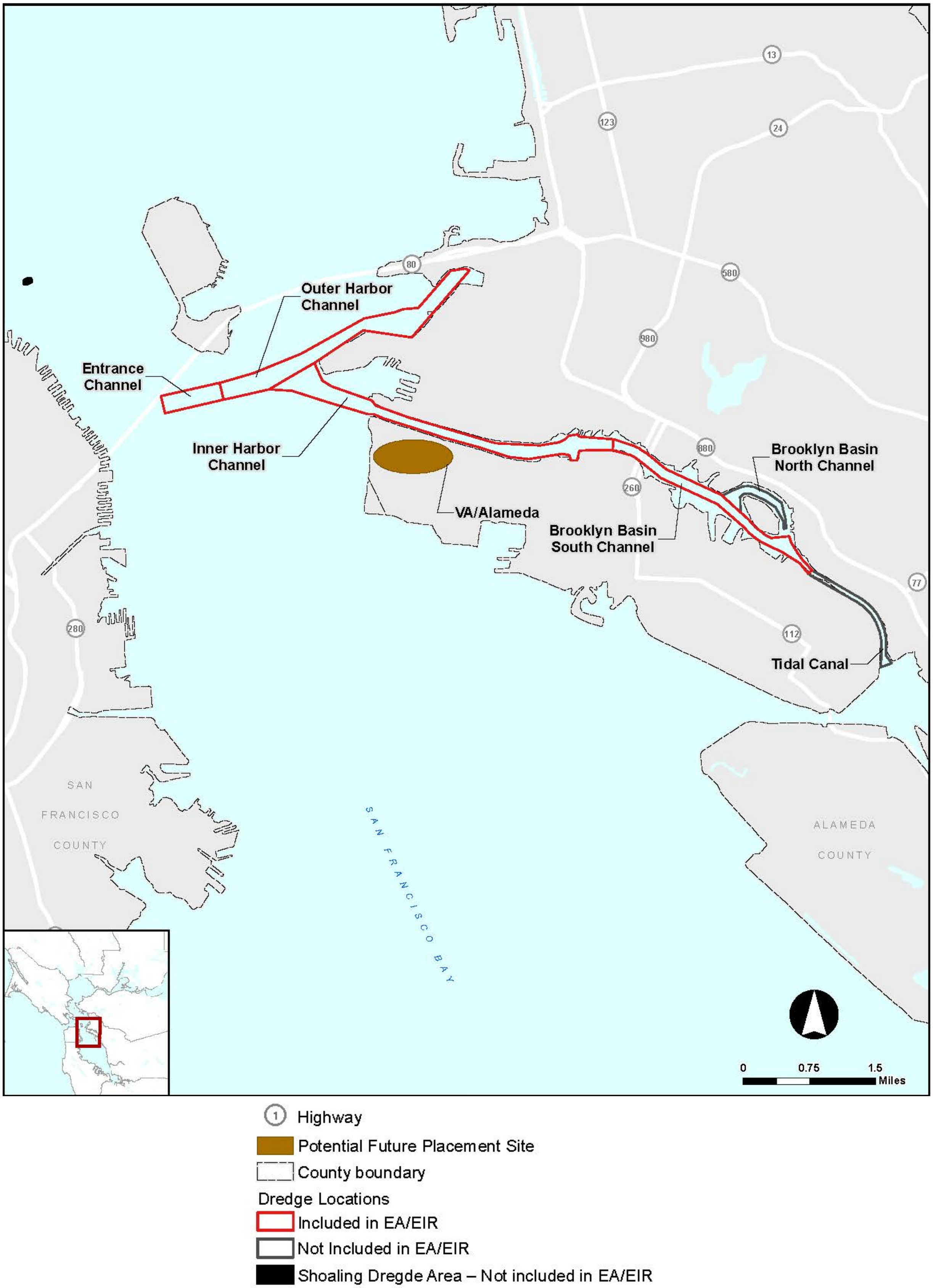

Figure 3. Oakland Harbor

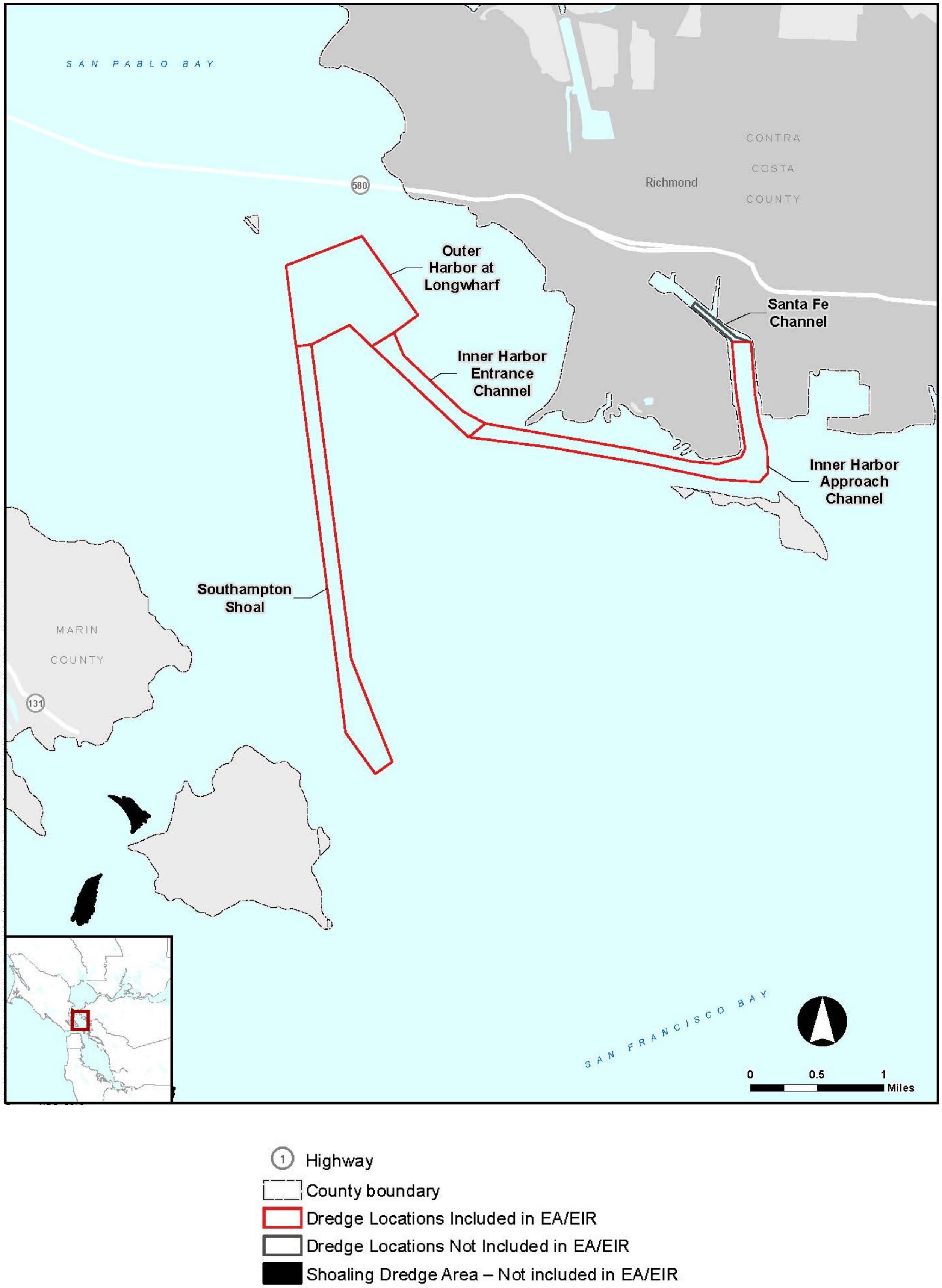

Figure 4. Richmond Harbor

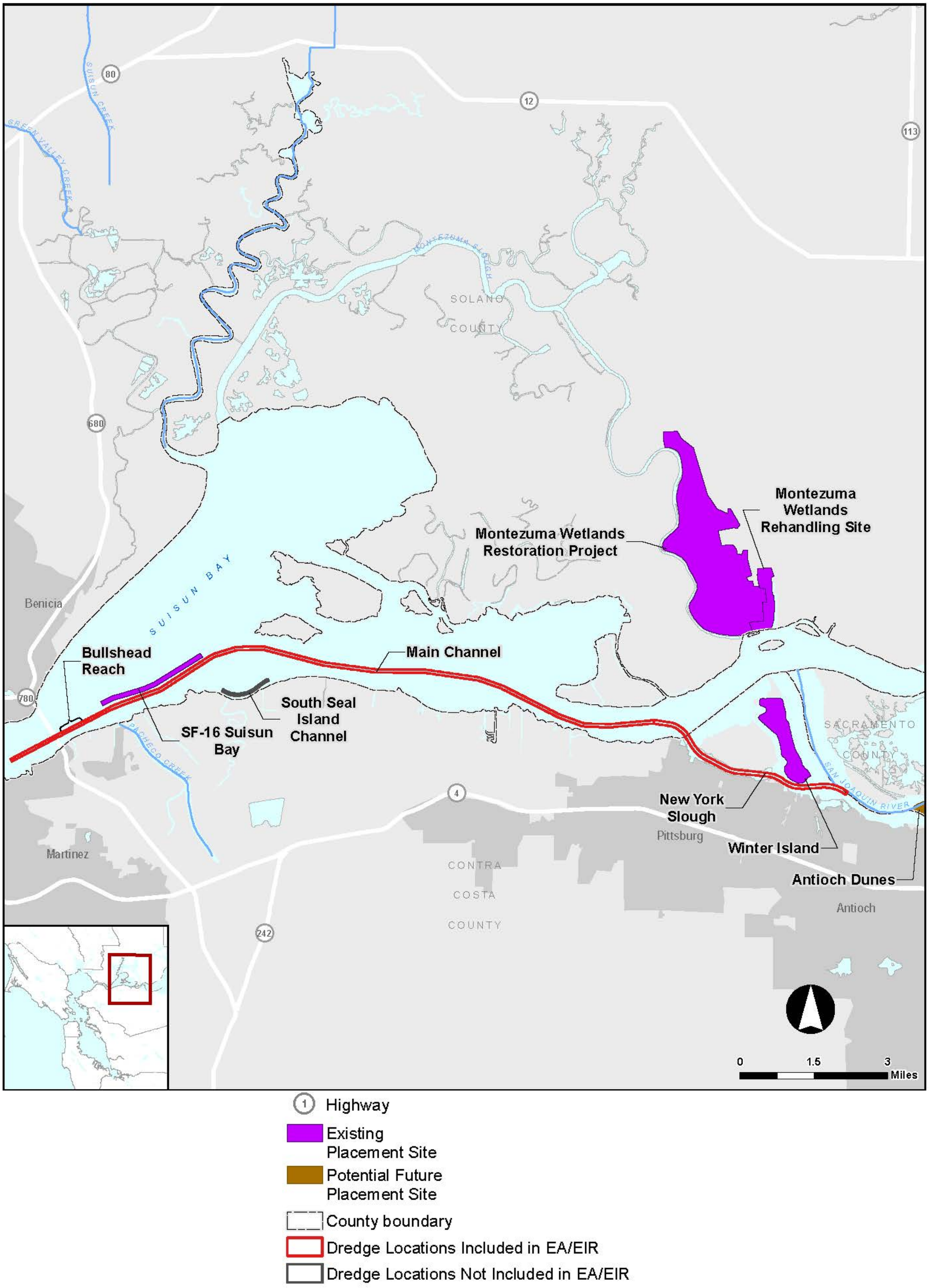

Figure 5. Suisun Bay Channel and New York Slough

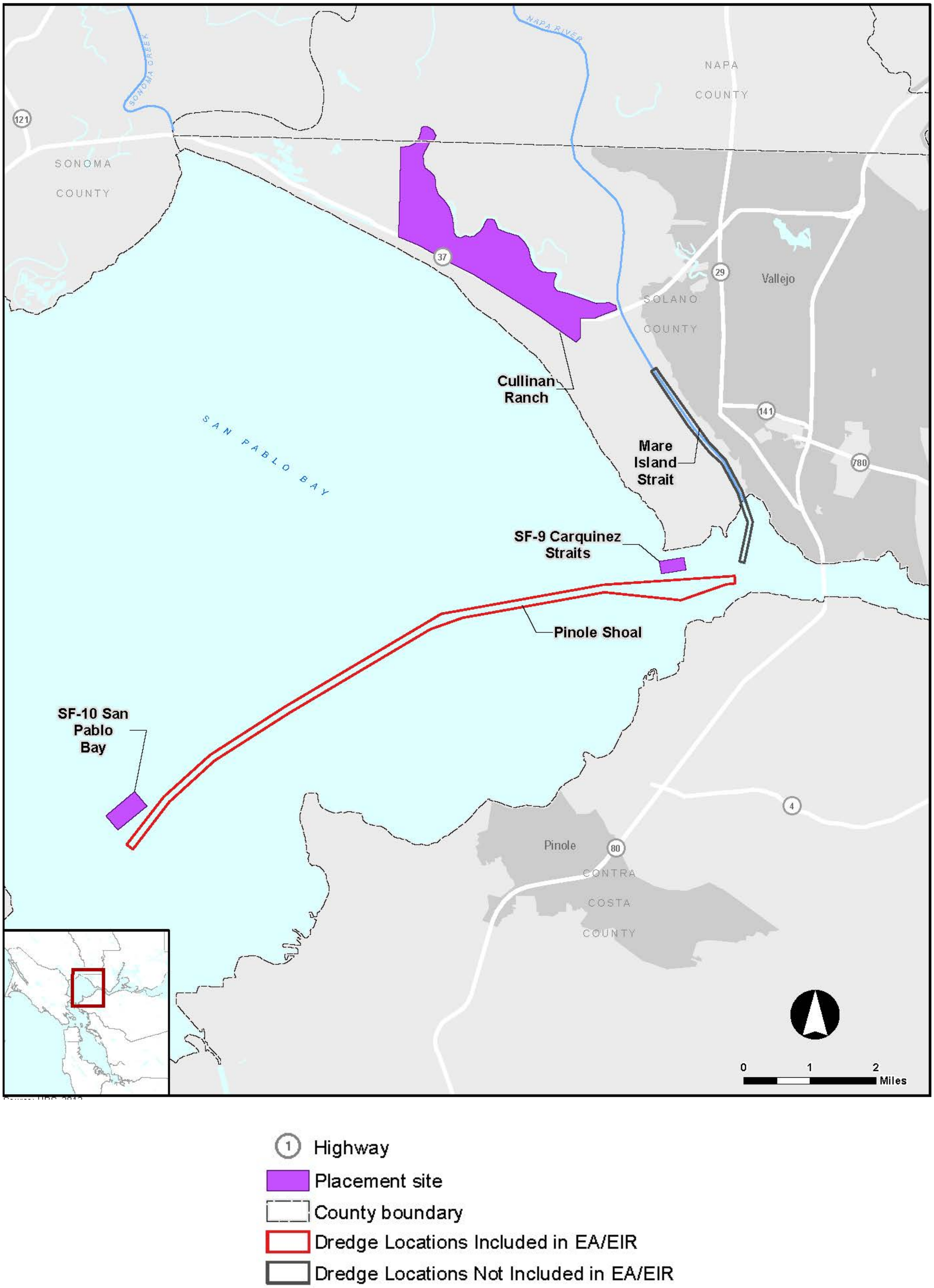

Figure 6. Pinole Shoal

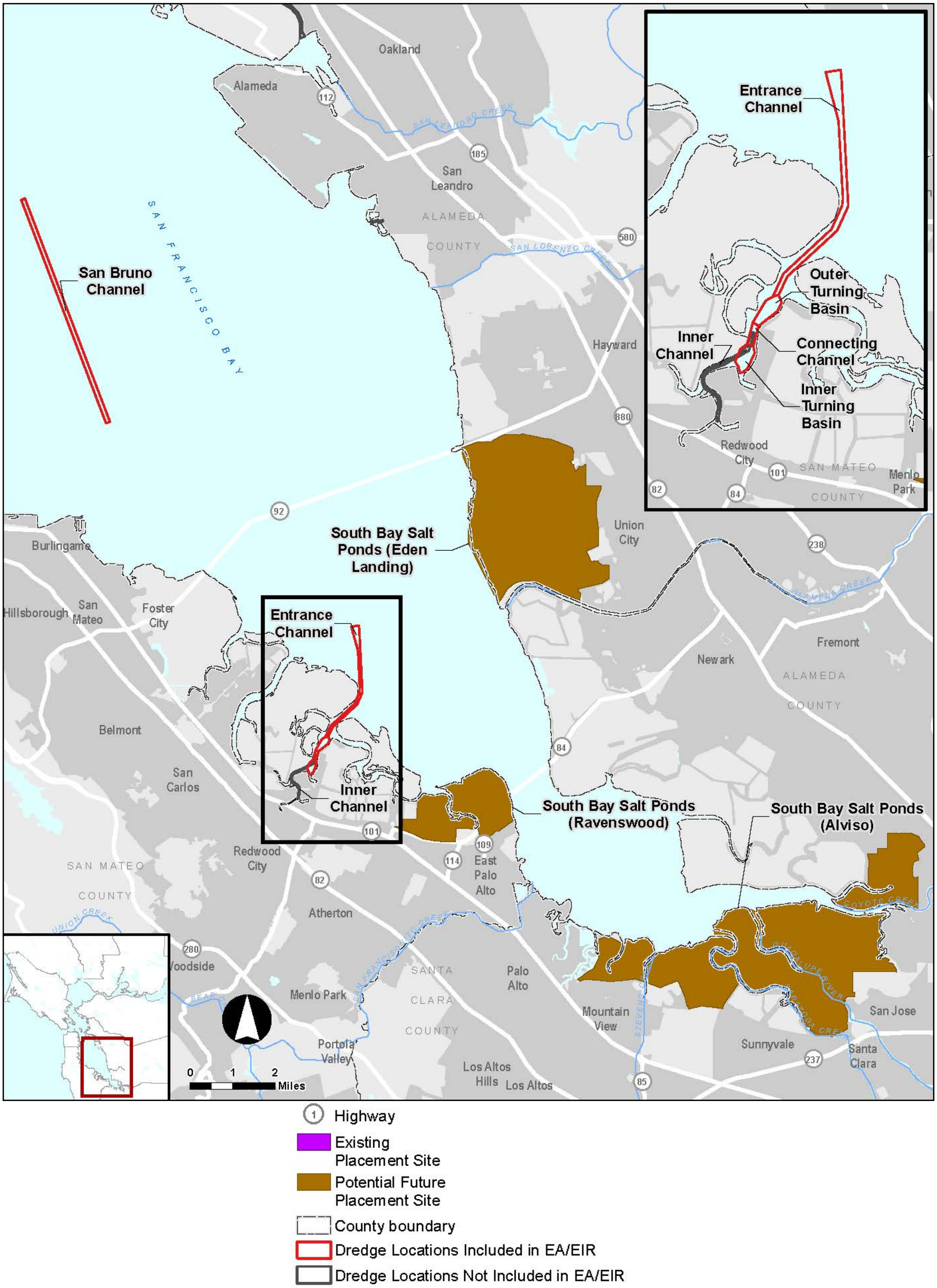

Figure 7. Redwood City Harbor

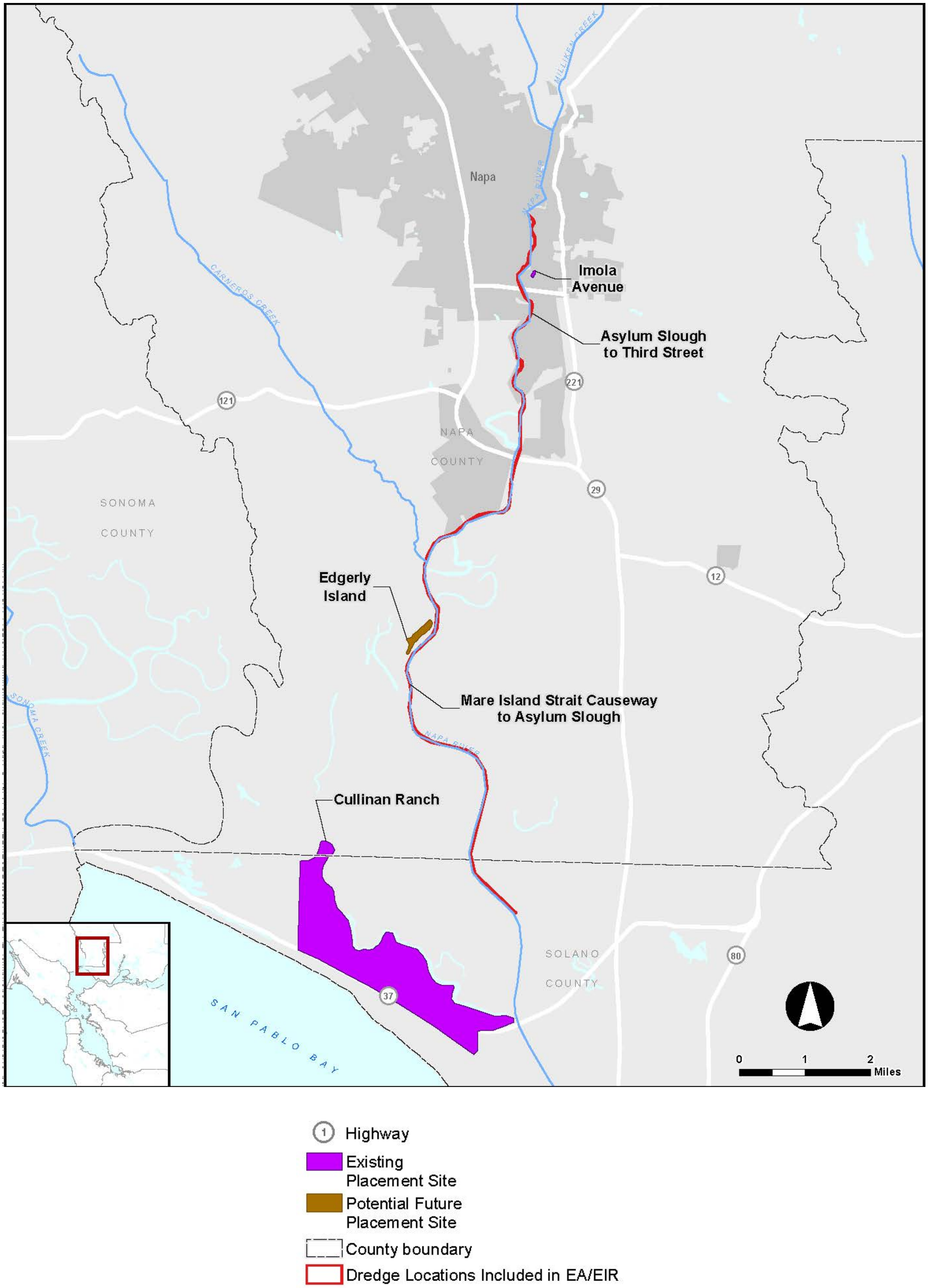

Figure 8. Napa River Channel

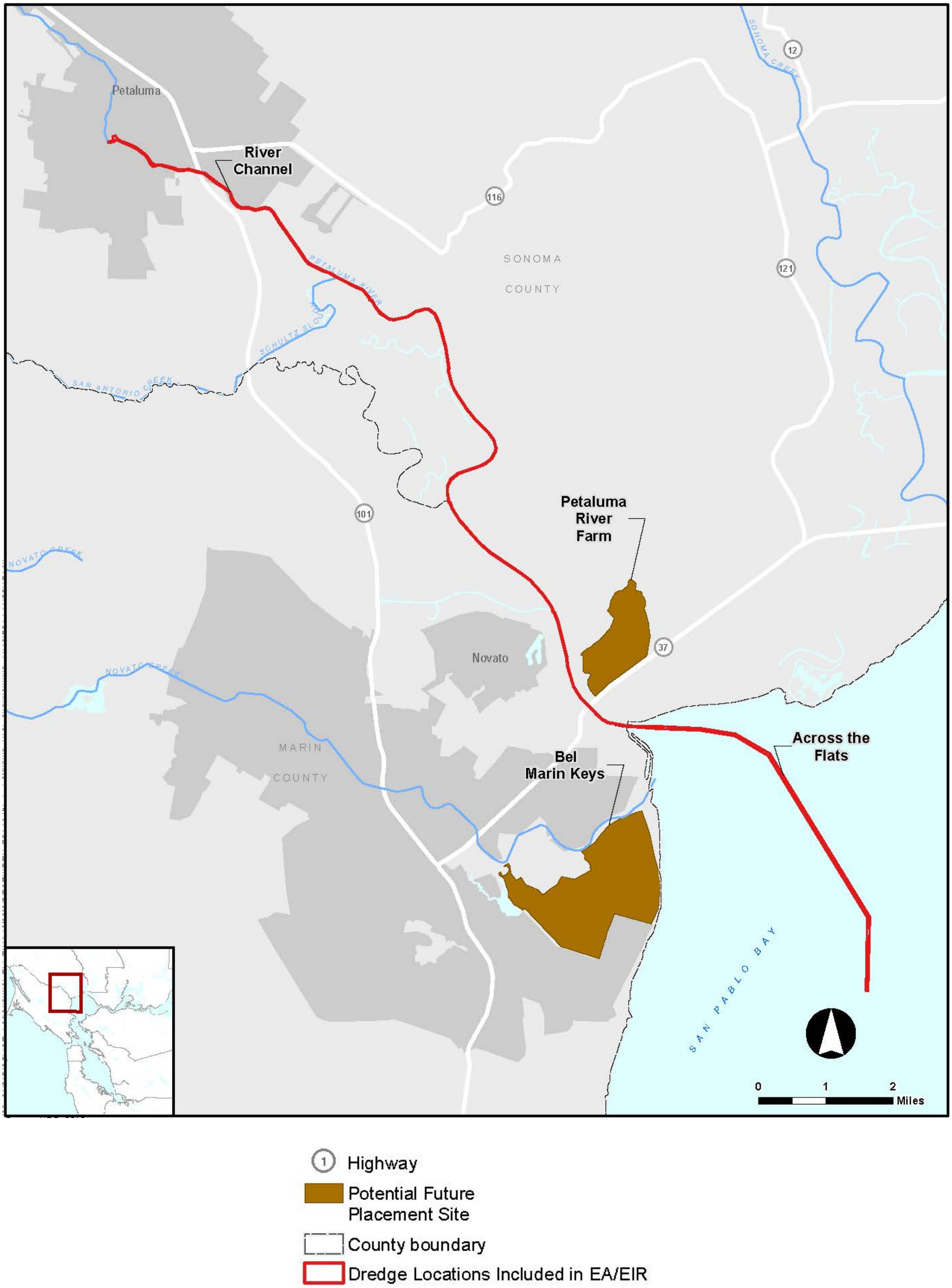

Figure 9. Petaluma River Channel

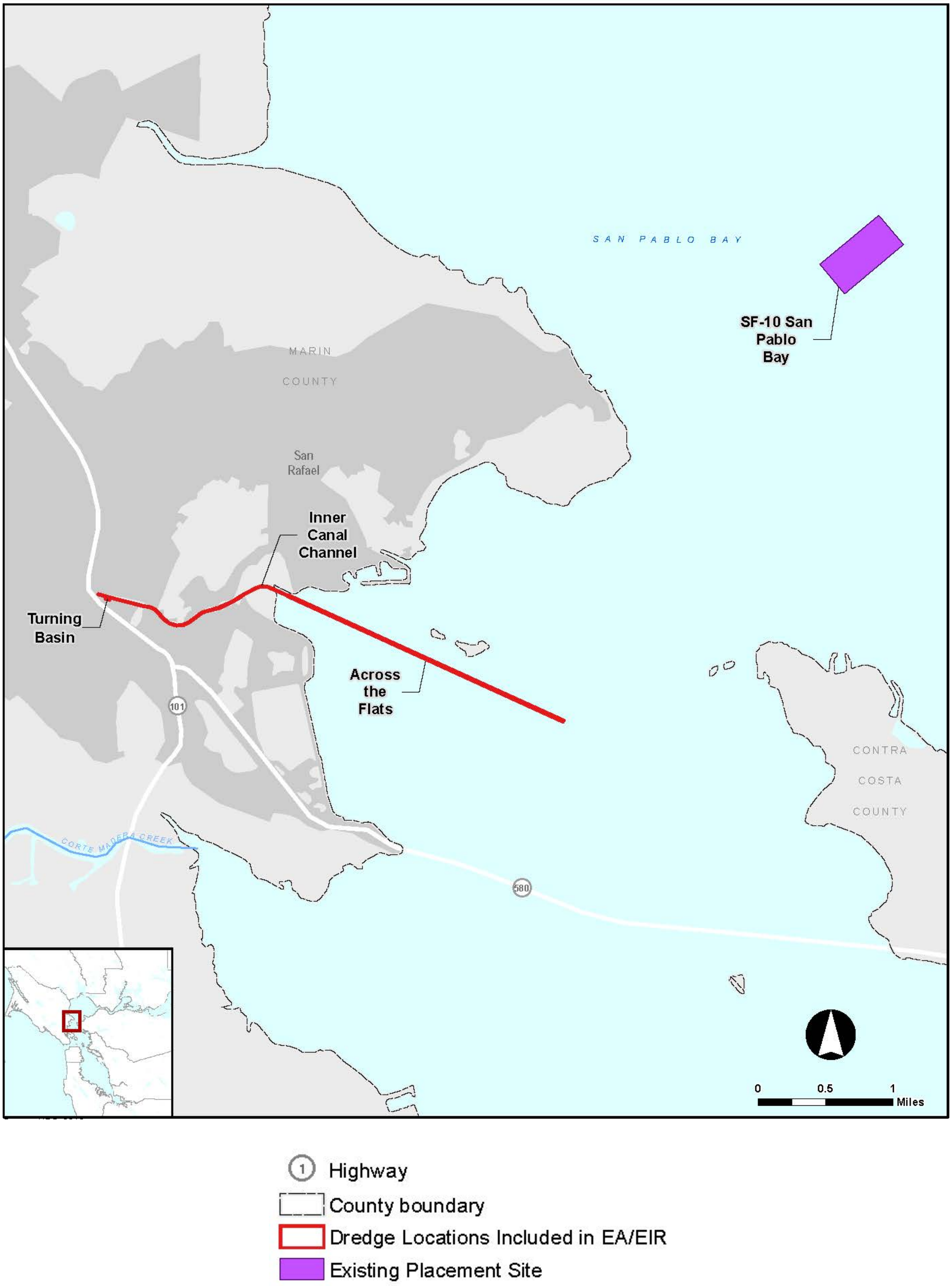

Figure 10. San Rafael Creek Channel

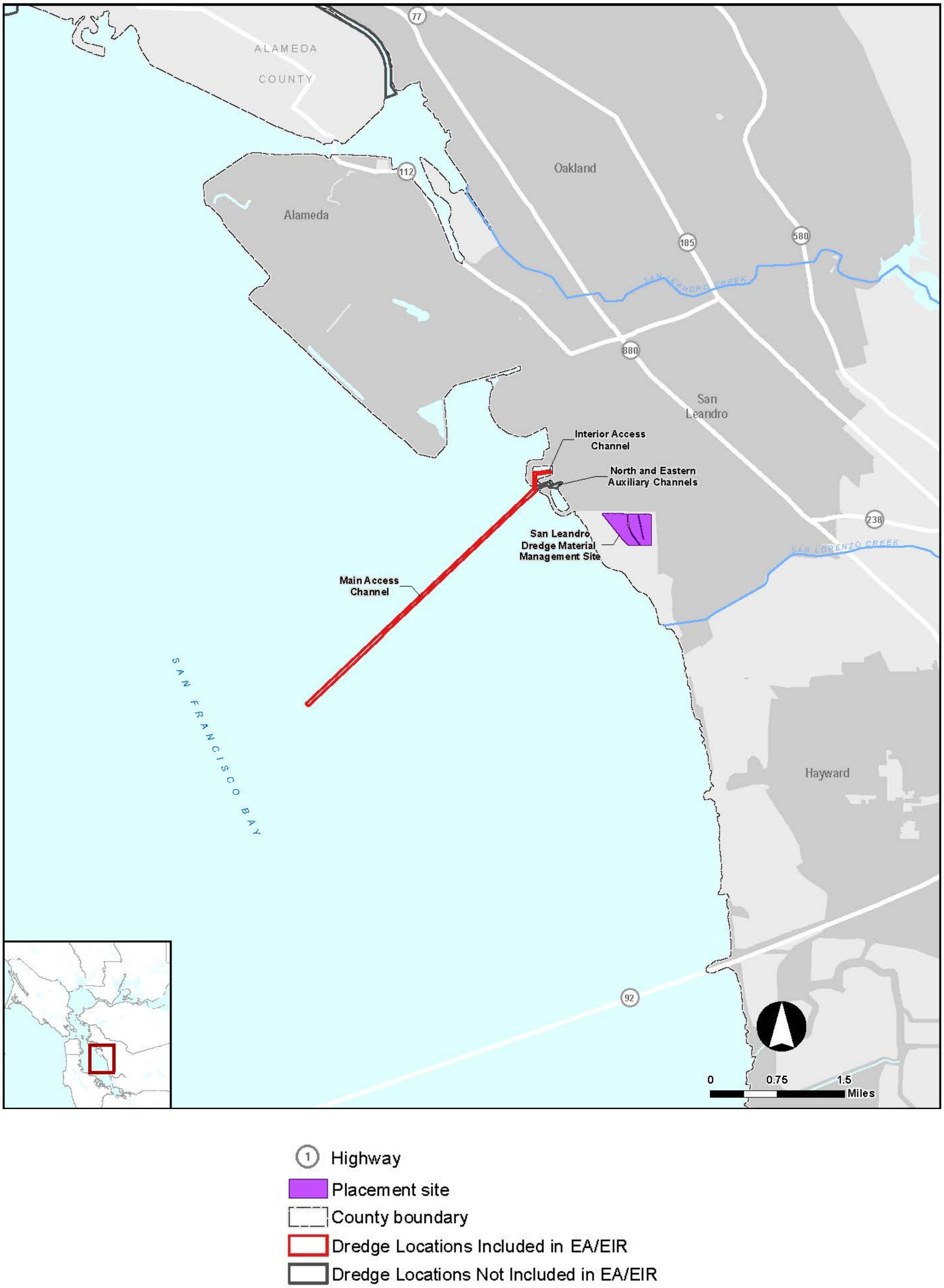

Figure 11. San Leandro Marina (Jack D. Maltester Channel)

APPENDIX B

Comments Received

DEPARTMENT OF THE ARMY
SAN FRANCISCO DISTRICT, U.S. ARMY CORPS OF ENGINEERS
1455 MARKET STREET
SAN FRANCISCO, CALIFORNIA 94103-1398

April 17, 2015

Executive Office

Mr. Bruce H. Wolfe
Executive Director
San Francisco Regional Water Quality Control Board
1515 Clay Street, Suite 1400
Oakland, California 94612-1413

Dear Mr. Wolfe:

The United States Army Corps of Engineers, San Francisco District (USACE) requested a Clean Water Act section 401 Water Quality Certification from the San Francisco Bay Regional Water Quality Control Board on February 4, 2015. On March 20, 2015, your agency issued the *Tentative Order – Reissued Waste Discharge Requirements and Water Quality Certification for U.S. Army Corps of Engineers, San Francisco District Maintenance Dredging Program, 2015 through 2019* (Tentative Order). We have reviewed the Tentative Order and respectfully submit our comments, which are provided below.

General Comments

1. Maintaining safe and efficient navigation in the Bay is one of the beneficial uses of water discussed in the Basin Plan. The Tentative Order is inconsistent with the Basin Plan because it fails to give the beneficial use of navigation equal weight with other beneficial uses of the Bay. As discussed below, navigation is vital to ensuring a strong regional and state economy.

2. It is USACE's primary mission to maintain safe navigation of its channels in the Bay. Maintaining the federal deep-draft navigation channels is vital to ensuring safe and efficient movement of good to and from Bay Area ports and harbors. Maintaining the shallow draft channels in vital to recreation and local economies.

3. The deep draft navigation channels in San Francisco Bay have more than 10,000 deep draft vessel trips annually. The goods-movement industry accounts for 51 percent of the total regional economic output and 32 percent of the total regional employment. The Bay Area ports and harbors play a major role in efficient movement of goods throughout the region, as well as in California and the West Coast of the United States. Ensuring that the federal deep-draft navigation channels, which provide navigation access to and from these ports and harbors, are maintained is vital to the economy of the region, California, and the West Coast of the United States.

4. With approximately 10,000 deep-draft vessel trips, including 3,000 to 5,000 oil tanker trips, being made to and from ports and harbors in the Bay Area, maintaining the deep-draft channels is vital to reducing the risk of vessel collisions, groundings, allisions, and oil spills.

5. Hopper dredges can easily maneuver out of the way of deep draft vessels. Clamshell dredges, on the other hand, take considerably longer to remove the anchor spuds and be moved by a tug out of the way of deep draft vessels. Each time a clamshell dredge has to move, it increases the duration of dredging, thus increasing the amount of time it takes to clear shoals.

6. We requested a Water Quality Certification pursuant to the federal Clean Water Act and not a Waste Discharge Requirement. A Waste Discharge Requirement is specific to the state Porter-Cologne Act and not a requirement of the federal Clean Water Act. Because there has been no clear and explicit waiver of sovereignty with respect to the Porter-Cologne Act, we do not have the authority to apply for and are not seeking a Waste Discharge Requirement. As such, in the title and throughout the document, please delete Waste Discharge Requirement (WDR) and replace with Water Quality Certification (WQC).

Tentative Order Scope

7. The Water Quality Certification should only apply to the discharge of dredge material and not the dredging action.

8. The Water Board only has jurisdiction on the placement of material dredged from the Main Ship Channel at the Ocean Beach Demonstration Site and not SF-8.

Tentative Order Long Term Management Strategy for Disposal of Dredged Material

9. With regard to suspended sediment in the Bay, the statement on page 2, item 6 states: "...in the mid-2000s, scientists from the U.S. Geological Survey identified a significant reduction in suspended sediment loading from the...river system. Less sediment in suspension and circulation within the Bay impairs the ability of shorelines, mudflats, and tidal wetlands to withstand erosion and inundation, especially as sea level rises." There are likely other environmentally sensitive and feasible possibilities for keeping sediment in the Bay through strategic placement.

10. On page 3, item 7, please delete "...calculated as 0.7 mcy times five years." Under the Long Term Management Strategy's Management Plan, allocations are only to be established if dredged material in-bay disposal volume limitations are exceeded. Because in-bay disposal limits have not been exceeded, it is not appropriate to unilaterally impose allocations in this Tentative Order.

Tentative Order Dredging Projects Summary

11. Table 1 (project summary table) was amended to constrain hopper dredge use per the reduced hopper dredge alternative. Please revise Table 1 per the project specifically requested in our Water Quality Certification application.

Tentative Order Impacts of Dredging and In-Bay Disposal

12. Page 10, item 16, please clarify paragraph 2 to read: "...the Corps must consult with the appropriate *federal* resource agency."

13. Pages 10 and 11, item 16, please clarify paragraph 3 to include: "There is no explicit waiver of federal sovereignty requiring federal agencies to comply with state listed special status species laws, including threatened or endangered species laws."

14. Please change "formal endangered species consultation" to "formal federal Endangered Species Act consultation" or "federal ESA."

15. Please delete the last paragraph starting with "This Order requires that the Corps comply with the programmatic LTMS work windows..." We do not agree that the Water Board has the authority to enforce the federal ESA under section 401 of the Clean Water Act. Further, as a federal agency, the USACE is not required to comply with the California Endangered Species Act or consult with the California Department of Fish and Wildlife (CDFW).

16. Pages 11 and 12, item 17: the discussion of the entrainment risk assessment is not accurate. As indicated by the United States Fish and Wildlife Service (USFWS) and USACE's Engineer, Research, and Development Center (ERDC), the estimates of entrainment are likely very high. Please update the Tentative Order discussion to include information presented in the draft EA/EIR (December 2014) and in the USFWS's 2014 Biological Opinion for maintenance dredging of Suisun Bay Channels.

17. Page 13, item 18: there is no evidence that the proposed project would substantially lessen the number of an endangered, rare, or threatened species. Further, as discussed in the draft EA/EIR, ERDC's entrainment risk assessment, and the 2014 Suisun Bay Biological Assessment, the entrainment study likely overstates the entrainment risk. Finally, the Tentative Order does not take into account the minimization measures to reduce entrainment risk or and the mitigation measure to compensate for potential entrainment. Please revise this statement accordingly, taking into account the opinions of the experts and the minimization and mitigation measures.

18. Page 13, item 18: the discussion of Fish & Game Code section 2053: "...the policy of the State that State agencies should not approve projects...which would jeopardize the continued existence of any endangered species...if there are reasonable and prudent alternatives available consistent with conserving the species." No analysis was conducted by the CDFW or the Water Board asserting that the proposed project would result in jeopardy to any listed species. Please delete this statement as no jeopardy analysis was conducted.

19. Page 13: the avoidance and minimization measures proposed would reduce the risk of entrainment to less-than-significant under the proposed action. Therefore, a reduced hopper dredge alternative is not warranted.

Tentative Order CEQA

20. Page 15, item 20, discusses the alternatives considered in the EA/EIR and states: Public Resources Code section 21002 declares the policy of the State that "agencies should not approve projects as proposed if there are feasible alternatives or feasible mitigation measures available which would substantially lessen the significant environmental effects of such projects." (See also, Cal. Code Regs., tit. 14, §§ 15041 ["A lead agency for a project has authority to require feasible changes in any or all activities involved in the project in order to substantially lessen or avoid significant effects on the environment"] and 15042 ["A public agency may disapprove a project if necessary in order to avoid one or more significant effects on the environment would occur if the project were approved as proposed."])

    The CEQA also defines *feasible.* "Feasible" means capable of being accomplished in a successful manner within a reasonable period of time, taking into account economic, environmental, social, and technological factors (§ 21061.1).

    As previously discussed with the Water Board staff and in the draft EA/EIR, the USACE considers a Tentative Order requiring a reduced hopper dredge alternative to exceed both the federal standard and the state's authority under section 401 of the Clean Water Act. Further, per 33 C.F.R. § 337.2, if the state imposes conditions which exceed those needed to meet the federal standard or when an agency requires special conditions or implementation of an alternative which the federal standard does not, such as a reduced hopper, dredging would be deferred until the issue is resolved. Deferred dredging, even temporarily, could result in adverse effects to the economy of the region and the state and, therefore, is not feasible.

21. The USACE disagrees with the statement "[t]here is no information in the record to date that indicates either Alternative 1 or Alternative 2 is infeasible." As discussed above, the USACE is not authorized to execute its maintenance dredging mission in a

manner which is inconsistent with the federal standard. The federal standard makes the reduced hopper dredge alternatives infeasible.

Tentative Order CEQA Findings

22. To the extent that the following statement is premised to the reduced hopper dredge alternatives and fails to fully account for economic considerations, we disagree with the statement on page 17: "The Water Board has considered and balanced the economic, legal, social, technological, and other benefits of this Order. The Water Board finds that the unavoidable adverse impacts are acceptable due to overriding concerns." As discussed above, navigation in the San Francisco Bay Area is vital to the regional and state economy. The potential to defer dredging could have significant adverse impacts on the regional and state economy.

23. We agree with the Water Boards finding: "[m]aintaining the federal channels to their regulatory depths is critical to the region's maritime trade and the regional and national economies." However, we are concerned that a reduced hopper dredge alternative would significantly increase the time it takes to remove shoals from the channel. Further, the potential for deferred dredging, even temporarily, could result in significant adverse effects to the regional and state economies.

Tentative Order Dredging and Disposal Operations

24. Page 21, item 6: please clarify that the overflow restriction is waived for both mechanical and hopper dredging if the fine-grained content is less than 20 percent (i.e., the sediment is greater than 80 percent sand).

25. Page 21, item 6, please clarify the statement: "2) describe how the effectiveness of economic barge loading, i.e. total cubic yards of material placed into a scow, vs. amount of suspended sediment released to the Bay will be evaluated with and without overflow."

Tentative Order Protection of Special Status Species

26. It is not clear what the Water Board's expectation is if we do not receive additional Congressional appropriations to implement the phased-in reduction of hydraulic suction hopper dredging inside San Francisco Bay. Further, pursuant to the federal standard, the USACE does not have authority to request additional funds above the federal standard.

27. The phased-in hopper dredge reduction alternative presupposes that the Water Board has section 401 jurisdictions over dredging operations, as opposed to only the discharge of dredged material. Pursuant to federal law, the Water Board only

has 401 jurisdiction over discharges for which a federal license or permit is necessary. It is the position of the USACE that the Water Board does not have the jurisdictional authority to issue Provision 10. It is our position that the Water Board does not have the legal authority under the provisions of the Clean Water Act to regulate the methods by which the USACE undertakes its dredging activities. Section 401 of the Clean Water Act is a limited waiver of federal sovereignty. Pursuant to the plain language of this section, in order for the Water Board to be able to issue Water Quality Certification conditions, the entity seeking the certification must first be required to apply for a federal license or permit. Because under the USACE regulations implementing section 404 discharges into waters of the United States, there is no substantive requirement for the USACE (or any other entity) to obtain a permit to conduct dredging activities the Water Board has no jurisdiction over the methods by which the USACE accomplishes its dredging. See 33 C.F.R. §323.2 (d)(3)(ii). In other words the triggering mechanism which invokes section 401, the necessity of applying for a federal license or permit, does not exist. Therefore, there is no requirement to obtain a section 401 Water Quality Certification for the dredging activity.

This position is distinguished from the activity of actually discharging dredged material into San Francisco Bay. For those activities which involve an actual discharge and for which a section 404 permit would otherwise be required, the USACE acknowledges that the Water Board has jurisdictional authority to issue Water Quality Certification conditions reasonably associated with the discharge.

It should also be stressed that a fair reading of the Clean Water Act is that it establishes a regulatory scheme which will restore and maintain the chemical, physical and biological integrity of all navigable waters; and, ultimately, develop factors necessary for the protection and propagation of shellfish, fish and wildlife. Principally this is to be accomplished through the elimination of the discharge of pollutants. [See 33 U.S.C. §§1251, 1314 and 1370] Under this scheme, the United States Environmental Protection Agency develops criteria which are subsequently incorporated into its approved state-adopted water quality standards pursuant to 40 C.F.R. §131.5. This includes state Water Quality Certifications issued pursuant to section 401 of the Act. The point here is that the goals of the Clean Water Act are accomplished by the regulation or elimination of the discharge of pollutants. The regulatory scheme does not include within its provisions, regulations pertaining to the possible entrainment of fish. To the extent that Congress intends for this to be regulated, it is accomplished under the provisions of the federal Endangered Species Act. Accordingly, it is the opinion of the USACE that under the Basin Plan, the Water Board is without authority to establish conditions which purport to limit the dredging methods chosen by the USACE.

28. Please delete item 13, "Entrainment Monitoring for Implementation of Reduced Hopper Dredging Option 10a" on page 25. For reasons discussed above in item 26, the Water Board has no authority to require entrainment monitoring of hopper dredges.

Tentative Order Certification

29. Page 27, please delete: "...and with other applicable requirements of State law" or clarify which state laws are being complied with. As a federal agency, the USACE may only comply with those state laws for which Congress has waived Federal sovereignty.

30. Page 28, item 27: please delete reference to the Porter-Cologne Water Quality Control Act. As a federal agency, the USACE does not comply with the state Porter-Cologne Act.

31. This may be boiler plate language; however, if work accomplished under the rescinded order is challenged by a third party, what is the impact of the rescission?

Thank you for the opportunity to review and comment on Tentative Order. If you have any questions or require additional information, please contact Mr. Christopher Eng of Environmental Section A at (415) 503-6868 or Christopher.K.Eng@usace.army.mil.

A copy of this letter was sent to Brenda Goeden (BCDC), Brian Ross (USEPA), Robert Lawrence (USACE), Jim Starr (CDFW), Shannon Little (CDFW), Arn Aarrenberg (CDFW), and Becky Ota (CDFW).

Sincerely,

John C. Morrow
Lieutenant Colonel, US Army
District Engineer

April 20, 2015

Elizabeth Christian
San Francisco Bay Regional Water Quality Control Board
1515 Clay Street, Suite 1400
Oakland, CA 94612
Email: echristian@waterboards.ca.gov

Transmitted via Electronic Mail

Re: Tentative Order and Application for Reissued Waste Discharge Requirements and Clean Water Act Section 401 Water Quality Certification for U.S. Army Corps of Engineers San Francisco District 2015-2019 Maintenance Dredging Program

Dear Ms. Christian:

On behalf of San Francisco Baykeeper ("Baykeeper") and our over 3,000 members who use and enjoy the environmental, recreational, and aesthetic qualities of San Francisco Bay and its surrounding tributaries and ecosystems, I respectfully submit these comments for consideration by the San Francisco Regional Water Quality Control Board ("Regional Board") in opposition to the proposed Tentative Order ("TO") and Application for Reissued Waste Discharge Requirements and Clean Water Act Section 401 Water Quality Certification ("Certification") for U.S. Army Corps of Engineers San Francisco District ("Corps") 2015-2019 Maintenance Dredging Program ("Project"). The Application and TO fail to meet the requirements of the California Code of Regulations Sections 3855 through 3864 pertaining to Water Quality Certifications and other applicable legal requirements. Thus, the Regional Board must deny Certification for the Project.

On January 20, 2015, Baykeeper submitted comments to the Corps and the Regional Board regarding the Draft Environmental Assessment (EA)/Environmental Impact Report (EIR) for Maintenance Dredging of the Federal Navigation Channels in San Francisco Bay, Fiscal Years 2015 – 2024 (SCH #2013022056) (hereafter, "Baykeeper's EIR Comments"). Baykeeper's EIR Comments are attached for your convenience as Exhibit A and are hereby incorporated by reference.

I. <u>The Application and TO Fail to Evaluate Numerous Impacts Related to Sediment Transport and Depletion.</u>

By failing to evaluate the impacts to San Francisco Bay and the outer coast from sediment depletion, the Application and TO for the Project are incomplete. The California Code of Regulations requires that any application for a water quality certification contain a "*full, technically accurate description*, including the purpose and final goal, *of the entire activity*," including the type of receiving water bodies and "the total estimated quantity of waters of the United States that may be adversely impacted temporarily or permanently by a discharge or by dredging." (23 Cal. Code Regs. §§ 3856(b), (h) [emphasis added].) The Corps' Application and TO fail to consider current scientific evidence showing a direct connection between the loss of sediment from the Bay ecosystem caused by dredging and other related activities and outer coast erosion, and fail to apply the applicable legal criteria for ocean disposal.

A. The Application and TO must consider recent scientific studies regarding sediment transport in San Francisco Bay.

The Application and TO improperly rely on the Policy Environmental Impact Statement/Programmatic Environmental Impact Report (EIS/EIR) completed in October 1998, which was also relied upon by the Draft EA/EIR. As thoroughly discussed in Baykeeper's EIR Comments, recent scientific studies have found an overall sediment deficit throughout the San Francisco Bay, which will be compounded by the Corps' dredging projects.[1, 2, 3, 4, 5, 6, 7, 8, 9, 10] (*See* Baykeeper's EIR Comments at 1-4.) This sediment deficit will likely result in shoreline erosion, wetland loss, and nutrient growth—none of which were properly considered in the EA/EIR or in the TO. As stated in Hein, J. *et al*. (2013), "With this causal link further effectively established…, the planning community can now more skillfully address the challenges of managing sediment in SF Bay in a manner that promotes the sustainability of open-coast beaches and submarine habitats."[11] Since the Corps has not made the Final EIR for the Project available to the public, it is unclear whether or not the Regional Board has reviewed this current literature. Without the incorporation and discussion of these recent scientific studies, the Application and TO rely on outdated, inaccurate science, which cannot provide the basis for the Regional Board's Certification for the Project.

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[1] Dallas, K. L. & Barnard, P. L., "Linking human impacts within the estuary to ebb-tidal delta evolution," 56 Journal of Coastal Research, 713-716 (2009) (attached hereto as Exhibit B).

[2] Dallas, K. L. & Barnard, P. L., "Anthropogenic influences on shoreline and nearshore evolution in the San Francisco Bay coastal system," 92 Estuarine, Coastal and Shelf Science, 195-204 (2011) (attached hereto as Exhibit C).

[3] Barnard, P. L. *et al*., "Integration of bed characteristics, geochemical tracers, current measurement, and numerical modeling for assessing the provenance of beach sand in the San Francisco Bay Coastal System," 345 Marine Geology, 181-206 (2013) (attached hereto as Exhibit D).

[4] Barnard, P. L. *et al*., "Sand transport in the San Francisco Bay Coastal System: An overview," 345 Marine Geology, 3-17 (2013) (attached hereto as Exhibit E).

[5] San Francisco Estuary Institute, Pulse of the Estuary 2009, Bay Sediments: Past a Tipping Point, 3 (2009), *available at* www.sfei.org/rmp/pulse.

[6] Erikson, L.H., Wright, S.A., Elias, E., Hanes, D.H., Schoellhamer, D.H., Largier, J., "The use of modeling and suspended sediment concentration measurements for quantifying net suspended sediment transport through a large tidally dominated inlet," 345 Marine Geology, 98–114 (2013) (attached hereto as Exhibit F).

[7] McGann, M., Erikson, L., Wan, E., Powell II, C., Maddocks, R.F., "Distribution of biologic, anthropogenic, and volcanic constituents as a proxy for sediment transport in the San Francisco Bay Coastal System," 345 Marine Geology, 115–144 (2013) (attached hereto as Exhibit G).

[8] Rosenbauer, R.J., Foxgrover, A.C., Hein, J.R., Swarzenski, P.W., "A Sr–Nd isotopic study of sand-sized sediment provenance and transport for the San Francisco Bay Coastal System," 345 Marine Geology, 145–153 (2013) (attached hereto as Exhibit H).

[9] Wong, F.L., Woodrow, D.L., McGann, M., "Heavy mineral analysis for assessing the provenance of sandy sediment in the San Francisco Bay Coastal System," 345 Marine Geology, 172–182 (2013) (attached hereto as Exhibit I).

[10] Hein, J., Mizella, K., Barnard, P., "Sand sources and transport pathways for the San Francisco Bay coastal system based on X-ray diffraction mineralogy," 345 Marine Geology, 154-169 (2013) (attached hereto as Exhibit J).

[11] *Id.* at 163.

B. The Application and TO must conduct a full analysis of ocean dumping criteria.

The TO finds that it is "in the public interest to encourage beneficial reuse of suitable dredged material as one component of regional adaptation to climate change and reduced suspended sediment loading of the Bay." (TO at 2.) Baykeeper thanks the Regional Board for designating habitat restoration beneficial reuse as the preferred placement sites for most of the Project. However, Baykeeper is concerned that the Regional Board has failed to use the fullest extent of its authority to protect the water quality of San Francisco Bay by failing to compel the Corps to correctly evaluate the federal standard for placement sites. In particular, the Application and TO fail to fully analyze ocean dumping criteria, which may artificially weigh the federal standard for placement sites in favor of ocean disposal rather than beneficial reuse.

As discussed in Baykeeper's EIR Comments, the Corps improperly defines the federal standard as the least-costly dredged material disposal or placement alternative, citing only 33 C.F.R. § 335.7, and placing an improper emphasis on cost. (*See* Baykeeper's EIR Comments at 4-7.) The Regional Board should require the Corps to conduct a complete evaluation to include an analysis of the ocean dumping criteria under the Marine Protection, Research and Sanctuaries Act. (*See* 40 C.F.R. Parts 220-228.) Ocean dumping criteria contained in 40 C.F.R. Part 227, titled "Criteria for the Evaluation of Permit Applications for Ocean Dumping of Materials," requires the evaluation of the need for ocean dumping and the consequences of using ocean disposal, all of which must be incorporated into the Corps' placement site analysis. In order to ensure that the Corps complies with the Regional Board's preferred placement sites and engages in beneficial reuse to the greatest extent possible, Baykeeper urges the Regional Board to require the Corps conduct a full analysis of ocean dumping, beyond mere costs. The Regional Board cannot certify the Project until the Corps conducts a full analysis under both 33 C.F.R. § 335.7 and 40 C.F.R. Part 227.

II. The TO Fails to Adequately Protect Special Status Species.

While Baykeeper thanks the Regional Board for conditioning the Project to protect Delta smelt and Longfin smelt, these conditions are inadequate and must be made more stringent. The California Code of Regulations requires that conditions be added to any certification "to ensure that all activities will comply with appreciable water quality standards and other appropriate requirements." (23 Cal. Code Regs. § 3859(a).) Here, the Regional Board conditioned Certification of the Project on the limitation of hydraulic suction hopper dredging inside San Francisco Bay beginning in 2017 to reduce entrainment of Delta and Longfin smelt.

However, recent abundance numbers for the Delta smelt have been at historic lows and the species is on the brink of extinction.[12] Baykeeper is extremely concerned about the fragile state of this species, and urges the Regional Board to strengthen the conditions in the TO and require that mechanical dredging be phased-in immediately. In particular, waiting to begin the phase-out of hopper dredging until 2017 could result in the imminent extinction of the Delta smelt, especially given model estimates showing that "up to approximately 29 percent of the median annual population abundance"

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[12] *See* "News worsens for rare Delta fish; Smelt's decline reflects health of estuary as a whole," Stockton Record (Apr. 18, 2015), *available at* http://www.recordnet.com/article/20150418/NEWS/150419726/101095/A_NEWS.

of Delta smelt are entrained during hydraulic dredging activities. (TO at 12.) The delay of this measure "due to the Corps' three-year budget process for its operations and maintenance program" (TO at 23) is irrelevant and inconsistent with the purposes of the Endangered Species Act. (*See TVA v. Hill*, 437 U.S. 153 (1978) ["[t]he plain intent of Congress in enacting [the ESA] was to halt and reverse the trend toward species extinction, whatever the cost"].) Certification of the Project cannot be approved without additional measures to protect species struggling to survive.

III. <u>The Final EIR/EA Has Not Been Made Public.</u>

As a procedural point, the final EA/EIR ("FEIR") for the Project is not publicly available, so Baykeeper is unable to assess whether the Corps and the Regional Board responded to Baykeeper's EIR Comments, and whether the forthcoming analysis in the FEIR has been supplemented in response to our criticisms. The TO states that "[t]he Water Board received and evaluated comments on the draft EIR from public agencies and the other interested parties. Responses to comments received during the comment period have been provided. The Water Board has considered, certified, and approved the final EIR (FEIR) . . . ." (TO at 14.) If the FEIR exists, it is being improperly kept from public review. Requiring the public to comment on Certification prior to the public release of the FEIR upon which Certification relies is entirely inappropriate and contrary to the public's right to be involved in the environmental review process.

IV. <u>The Draft EA/EIR Improperly Defines the "No Project Alternative."</u>

As stated in the TO, the Draft EA/EIR defines the "No Project Alternative" as the continuation of "current maintenance dredging practices for the projects it maintains in San Francisco Bay." (TO at 14.) The Regional Board based this determination on CEQA Guidelines section 15126.6(e)(3)(A), which provides that "when the project is the revision of an existing land use or regulatory plan, policy or ongoing operation, the no project alternative will be the continuation of the existing plan, policy or operation into the future." (*Id*.) However, this provision of the Guidelines is not applicable to the Corps' maintenance dredging practices.

As the CEQA Guidelines provide, "[t]he purpose of describing and analyzing a no project alternative is to allow decisionmakers to compare the impacts of approving the proposed project *with the impacts of not approving the proposed project*." (Guidelines § 15126.6(e)(1) [emphasis added].) Here, a decision to reject the Corps' proposed maintenance dredging project for years 2015 through 2024 would not allow for the continuation of current maintenance dredging projects because the Corps would not have the required permits or approvals to conduct such activities. (*See, e.g.,* TO at 15-18 [discussing CEQA Findings required for issuance of Certification]; Draft EA/EIR at ES-1 ["This document is also intended to fulfill the Regional Water Board's CEQA compliance requirements for issuance of a 10-year WQC to USACE"].) Thus, the "No Project Alternative" in the EA/EIR must be revised to reflect such realities. Without this revision, the draft EA/EIR is fundamentally flawed and does not meet the basic purposes of CEQA "to inform the public and decision makers of the consequences of environmental decisions before those decisions are made." (*Woodward Park Homeowners Assn., Inc. v. City of Fresno* (2007) 150 Cal. App. 4th 683, 691.)

V. <u>Conclusion.</u>

Baykeeper strongly urges that the proposed Waste Discharge Requirements and Clean Water Act Section 401 Water Quality Certification for U.S. Army Corps of Engineers San Francisco District 2015-2019 Maintenance Dredging Program be denied until the deficiencies discussed above have been remedied. A healthy San Francisco Bay which is resilient to sea level rise and other phenomenon related to climate change requires the Corps to utilize beneficial reuse to the greatest extent possible. While the proposed conditions on hopper dredging is a step in the right direction to protect Delta and Longfin smelt, these conditions must be strengthened to make sure that these fragile species survive. As currently drafted, Baykeeper opposes the TO and urges the Regional Board to deny Certification.

Sincerely,

George Torgun

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George Torgun
Managing Attorney
San Francisco Baykeeper

Exhibit A

SAN FRANCISCO BAYKEEPER®

January 20, 2015

US Army Corps of Engineers and
San Francisco Bay Regional Water Quality Control Board
c/o Linda Peters, Project Manager
URS Group Inc.
One Montgomery Street, Suite 900
San Francisco, California, 94104-4538

Via electronic mail to linda.peters@urs.com

RE: Draft Environmental Assessment (EA)/Environmental Impact Report (EIR) for Maintenance Dredging of the Federal Navigation Channels in San Francisco Bay, Fiscal Years 2015 – 2024 (SCH #2013022056)

Dear Ms. Peters:

On behalf of San Francisco Baykeeper and our over 3,000 members who use and enjoy the environmental, recreational, and aesthetic qualities of San Francisco Bay and its surrounding tributaries and ecosystems, we respectfully submit these comments for consideration by both the U.S. Army Corps of Engineers and the San Francisco Regional Water Quality Control Board. The principal purpose of these comments is to improve the level of review and analysis in the EA/EIR regarding impacts from the proposed maintenance dredging to sediment quantities in and around San Francisco Bay. In light of decreasing sediment supply to San Francisco Bay, and at a time when protection of coastal and Bay shorelines is of the upmost importance in the face of rising sea levels, the proposed project must do more to conserve and beneficially reuse materials dredged from the Bay floor, that are of suitable quality. Such is the multi-agency policy recommendation of the Long Term Management Strategy ("LTMS") which calls for the maximization of in-Bay beneficial reuse, and the minimization of deep ocean disposal. Unfortunately, the proposed project does not further this policy, placing too great a reliance on the "least costly" alternative, while giving inadequate consideration to both regional policies and federal regulations. Accordingly, we ask that the EA/EIR be revised to evaluate: (1) the proposed project's impacts to regional sediment supplies; (2) the appropriateness of proposed placement sites pursuant to federal ocean dumping criteria; and, (3) a project alternative that would minimize deep ocean disposal and maximize beneficial reuse, consistent with the LTMS goals.

I. The EA/EIR Fails to Evaluate Numerous Impacts Related to Sediment Depletion.

Recent scientific study has found an overall sediment deficit throughout the San Francisco Bay, with resulting implications for shoreline erosion, wetland loss, sea level rise adaptation, and nutrient growth.

[1,2,3,4] Unfortunately, these emerging and interrelated issues are nowhere mentioned in the EA/EIR. By dumping up to 4.8 million CY of dredged material per year from San Francisco Bay, into the deep ocean disposal site (EA/EIR 1-34), the proposed project significantly causes and contributes to the growing sediment deficit in the Bay. Accordingly, the proposed project's plan to ship these tremendous quantities of often valuable sediment 50 miles offshore must be reevaluated in light of the existing environmental conditions of sediment deficiency in the Bay, projected sea-level rise, and the significant impacts resulting from the further loss of sediment via deep ocean disposal.

Extant scientific literature extensively documents impacts throughout the Bay Area related to sediment deficiency, which impacts are not disclosed or analyzed in the EA/EIR. For example, in 2009, the San Francisco Estuary Institute's *Pulse of the Estuary, Bay Sediments: Past a Tipping Point*[5] summarized these findings:

> *. . . between 1998 and 1999 it appears that the Bay passed a tipping point at that time due to the depletion of a pool of easily erodible sediment that had been slowly moving through the watershed ever since the Gold Rush. In 1999 this pool seems to have been exhausted, and suspended sediment concentrations fell by 40%.*
>
> *This shift to clearer waters is affecting the ecology and management of the Bay in many ways. Ecologically, the Bay shifted from a system where photosynthesis by phytoplankton was limited by a lack of light penetration in the murky waters, to one where phytoplankton abundance has been increasing (page 53) and represents a growing concern. Water quality managers now must pay closer attention to the potential for nutrient pollution to cause the problems associated with excessive algal production that are common in many other estuaries, such as Chesapeake Bay.*
>
> *…With a smaller natural supply of sediment, there will be an even greater demand for re-using dredged sediment in restoration projects. In light of all of these changes, the Long-Term Management Strategy for dredged material may need to be updated.*
>
> *…The increase in Bay water clarity in recent years has significant ramifications for dredging, wetland restoration, water quality, and ecology. The Long-Term Management Strategy (LTMS) for Dredging and Dredged Material Disposal in San Francisco Bay was developed in the early 1990s, before the 1999 decrease in suspended sediment. Lower SSC reduces deposition, which in*

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[1] Dallas, K. L. & Barnard, P. L., 2009. Linking human impacts within an estuary to ebb-tidal delta evolution. Journal of Coastal Research, Volume 56, pp. 713-716.
[2] Dallas, K. L. & Barnard, P. L., 2011. Anthropogenic influences on shoreline and nearshore evolution in the San Francisco Bay coastal system. Estuarine, Coastal and Shelf Science, Volume 92, pp. 195-204.
[3] Barnard, P. L. et al., 2013. Integration of bed characteristics, geochemical tracers, current measurement, and numerical modeling for assessing the provenance of beach sand in the San Francisco Bay Coastal System. Marine Geology, 345, pp.181-206.
[4] Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E. & McKee, L. J., 2013. Sand transport in the San Francisco Bay Coastal System: An overview. Marine Geology, 345, pp.3-17.
[5] San Francisco Estuary Institute. 2009. *Pulse of the Estuary 2009, Bay Sediments: Past a Tipping Point*. See p. 3. Available at www.sfei.org/rmp/pulse

turn reduces the amount of maintenance dredging that is needed. Lower SSC may also make the in-Bay dredged material disposal sites more dispersive and increase their capacity. Bay disposal sites may be able to accommodate more material, reducing the need for costly ocean disposal.

The *Pulse* article's references to the LTMS here are critical. Instead of relying on updated information, the present EA/EIR continues to rely on the analysis and policies provided for in the now-outdated 1998 LTMS EIR. The EA/EIR only considers sediment impacts related to turbidity and sediment quality, adverse impacts that augur in favor of placement at DODS. (EA/EIR 3.4-13.) The EA/EIR acknowledges that "LTMS agencies are assessing potential changes in the program's implementation to accommodate changing or adding flexibility to in-Bay disposal volume limits, encouraging more beneficial reuse and new kinds of beneficial reuse" (EA/EIR 1-5), but this only serves to confirm that the information and policies provided in the 1998 LTMS EA/EIR are in fact outdated. Based on significant new information since that time, the LTMS EIS/R does not provide relevant impact analysis for today's proposed project, and should not be incorporated into or tiered from to support analysis in this EA/EIR. (Pub. Resources Code § 21166; 40 C.F.R. § 1502.9(c).)[6] The project changes designed to maximize beneficial reuse and minimize deep ocean disposal need to be analyzed, both in the present EA/EIR, and pursuant to 40 C.F.R § 220 et seq., as discussed below, before the proposed project may be approved.

More recent scientific study presented in a special issue of Marine Geology reinforces and adds to the understanding of Bay sediment dynamics and depletion. The San Francisco Regional Water Quality Control Board has called this publication "a cornerstone of our federal, state, and local agency collaborative monitoring program . . . . It continues to inform major management actions and decisions on water-quality control, dredging, and habitat restoration."[7] A summary of findings from the special report states:

Over the last century, a minimum of 200 million m3 of sediment has been permanently removed from the San Francisco Bay Coastal system through dredging, aggregate mining, and borrow pit mining.

. . .

Dredging removes about 3 million m3/year of sediment out of navigation channels and from other channel and berth maintenance projects, with the majority of this material permanently removed from the San Francisco Bay Coastal System via deep-water disposal in the Pacific Ocean (citations), roughly equivalent to the annual sediment supply from the Central Valley.

. . .

Suspended sediment in San Francisco Bay limits light availability, photosynthesis, and phytoplankton growth. Decreased suspended-sediment concentrations (SSC) after 1999 has contributed to increased chlorophyll concentrations, larger spring phytoplankton blooms, and

[6] Moreover, to the extent the EA/EIR attempts, for these analyses, to rely on any of the numerous EIRs and/or other policy documents incorporated by reference, it has failed to do so, as no summary or information from such past documents is provided in the present EA/EIR as to the project's consistency with federal ocean dumping criteria. (Pub. Resources Code § 21061; 14 Cal Code Regs § 15150(c).)

[7] http://ca.water.usgs.gov/news/2014/TravelsWithSediment.html

> *reoccurrence of autumn blooms. Reduced SSC may be one of several factors contributing to a collapse of several San Francisco Bay estuary fish species that occurred around 2000.*
> *. . .*
> *Rising sea levels over the 21st century will increase the frequency of extreme water level events in San Francisco Bay, placing additional stress on the San Francisco Bay Coastal System's tidal marshes (including massive restoration projects currently underway), levees, shorelines, and ecosystems. . . . These changes will undoubtedly impact circulation patterns and shift peak sediment loads to earlier in the year. . . . [W]eltands are particularly vulnerable, as they would require a total sediment input (i.e., organic matter and inorganic sediment) of up to 10.1 Mm3/year (~2.6 cm/yr) by 2100 to keep pace with the higher projections of sea level rise.*[8]

Unfortunately, the EA/EIR almost entirely fails to consider these findings, citing to this study in less than one full paragraph out of the entire 345 page environmental document, without any discussion of the adverse *consequences* of past, ongoing, and future sediment depletion, nor any consideration of any contributions the proposed project may have to these impacts by removing up to 4.8 million CY of dredged material per year from San Francisco Bay. (EA/EIR 3.4-8.) Given that this amount is greater than the average annual sediment load to San Francisco Bay from the Central Valley, the project results in significant sediment depletion from the Bay, with associated impacts to shoreline erosion, wetland loss, sea level rise adaptation, nutrient growth, and others that must be evaluated here. The complete failure to mention these effects renders the EA/EIR insufficient to fulfill the basic informational requirements of NEPA and CEQA. (*E.g.*, *Laurel Heights Improvement Ass'n v Regents of Univ. of Cal.* (1988) 47 Cal.3d 376, 404 *Mountain Lion* Coalition *v Fish & Game Comm'n* (1989) 214 Cal.App.3d 1043.)

Of some relevance, the EA/EIR does state that:

> *Beneficial reuse that has occurred at some of the existing placement sites provides protection against sea level rise. For example, the beneficial reuse of dredged material for wetland restoration provides additional protection against rising water levels because wetlands function as natural sponges that trap and slowly release surface and flood waters.* (EA/EIR 3.4-10.)

But the EA/EIR fails to acknowledge the converse, that a loss of sediment in the Bay via deep ocean disposal will deprive the Bay of this needed resource, whether protecting shorelines by natural accretion, or by beneficial reuse. Nor does the EA/EIR meaningfully evaluate any project changes or alternatives that would protect the region from ongoing and future sea level rise.

II. The EA/EIR Fails to Evaluate the Proposed Project Pursuant to Ocean Dumping Criteria.

Prior to approval, federal regulations require the ACOE to conduct a thorough evaluation of whether proposed placement sites are consistent with federal standards. The EA/EIR does not undertake any such analysis. While the EA/EIR does put forth a proposed action/project that generally seeks to

[8] Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E. & McKee, L. J., 2013. Sand transport in the San Francisco Bay Coastal System: An overview. Marine Geology, 345, pp.7-12.

continue existing practices, the federal regulations and sound public policy still require that established ocean dumping criteria be considered prior to the approval of any ocean dumping of dredge material. There can be no dispute that the proposed project would, in fact, approve ocean dumping of dredge materials, and evaluation of the criteria set forth in 40 C.F.R. § 220 et. seq. is therefore required prior to project approval.

The EA/EIR repeatedly, and, somewhat misleadingly, states that:

> *The federal standard is defined as the least-costly dredged material disposal or placement alternative consistent with sound engineering practices, and meeting the environmental standards established by the Section 404(b)(1) evaluation process or ocean dumping criteria (33 C.F.R. § 335.7).* (EA/EIR ES-7, ES-8, 1-3, 2-19, 2-21.)

This is an incomplete description of the standards that must be considered prior to approving ocean dumping of dredge material. Without setting forth all relevant criteria, the public and agency decision-makers will likely rely too heavily on the "least-costly" factor in selecting a dredge disposal location.

In fact, federal regulations require evaluation of additional criteria that are nowhere described or cited in the EA/EIR: 40 C.F.R. 220 et seq. "establishes the criteria to be applied by the Corps of Engineers in its review of activities involving the transportation of dredged material for the purpose of dumping it in ocean waters pursuant to section 103 of the [Marine Protection, Research, and Sanctuaries Act ("MPRSA")]." (40 C.F.R. § 220.1.) While sections 102(a) and 103 of the MPRSA contain numerous requirements for any approval of ocean dumping of dredge materials – also not discussed in the EA/EIR – the pertinent regulations continue:

> *The need for dumping will be determined by evaluation of the following factors:*
> *. . .*
> *(c) The relative environmental risks, impact and cost for ocean dumping as opposed to other feasible alternatives including but not limited to:*
>
> > *. . .*
> > *(4) Spread of material over open ground;*
> > *(5) Recycling of material for reuse;*
> > *. . .*
> > *(7) Storage [and,]*
>
> *(d) Irreversible or irretrievable consequences of the use of alternatives to ocean dumping.* (40 C.F.R. § 227.15)

None of these factors are mentioned or evaluated in the EA/EIR. The regulations continue, "[a] need for ocean dumping will be considered to have been demonstrated when a *thorough* evaluation of the factors listed in § 227.15 has been made." (40 C.F.R. § 227.16, emphasis added.) Here, the complete lack of any mention of these factors cannot be considered to be a thorough evaluation. Only after a thorough application of these criteria to a proposed project may the ACOE permit ocean dumping, and even then only after rendering an express determination that:

> *There are no practicable alternative locations and methods of disposal or recycling available, including without limitation, storage until treatment facilities are completed, which have less adverse environmental impact or potential risk to other parts of the environment than ocean dumping.* (40 C.F.R. § 227.17.)

As used elsewhere in the C.F.R. regarding dredge disposal, "practicable" means "available and capable of being done after taking into consideration cost, existing technology, and logistics in light of overall project purposes." (40 C.F.R. § 230.10.) This practicability standard establishes a more protective bar than the selection of the "least-costly" alternative as so often put forth in the EA/EIR.

On a number of occasions, the EA/EIR describes selection of placement sites in a way that departs from the criteria listed, above, and provided for by regulation. For example, the EA/EIR states that:

> *Transport costs factor largely into determining the federal standard; therefore, generally placement sites closest to the dredge site are the federal standard unless environmental considerations dictate selection of another location.* (EA/EIR 3.5-14.)

First, this statement places too heavy a reliance on the least-costly alternative, while providing no analysis of the "environmental considerations." And second, if transportation costs are so influential, how is the farthest distance disposal site, DODS, the most often used?

Elsewhere, the EA/EIR explains:

> *For maintenance dredging in the San Francisco Bay region, the range of placement options is limited to those that are relatively near the larger and medium sized dredge projects, and those that are technically feasible and cost effective for larger and medium sized operations.* (EA/EIR 1-6.)

However, this misstates the regulatory standard, since cost-effective is not the same as practicable ("capable of being done after taking into consideration cost, existing technology, and logistics in light of overall project purposes").

Later, the EA/EIR states that:

> *Typically, the federal standard placement site is used; however, at their own discretion, dredging contractors may use other permitted upland locations as an alternative to the disposal site or sites identified in a given solicitation for maintenance dredging contracts, as long as the cost of the site is comparable to the cost of the federal standard.* (EA/EIR 1-33.)

This, however, misapplies the federal standard, as cost is not the sole criterion. Moreover, this open-ended statement renders any stable project description illusory. The EA/EIR in fact identifies several existing and potential disposal sites located throughout the Bay, some of which are currently accepting sediment for beneficial reuse (EA/EIR Figure ES-1). Analysis regarding the feasibility of utilizing such locations, per federal regulations, however, is lacking. Permanent removal of dredged sediments poses a critical risk for current and future restoration projects and poses an incredible impediment to on-going restoration projects in the North and South Bay.

III. The Project Description, Purpose, Need, and Required Approvals are Inadequately Defined.

The EA/EIR generally purports to continue historic and ongoing dredge and placement activities in and throughout San Francisco Bay, but fails to provide necessary detail describing timing, location, volumes, placement locations, and required permits for future dredge activities to meaningfully comprehend the proposed project at issue. Instead, the EA/EIR generally assesses a series of project related by type and geographic scope, together in one EA/EIR in order to attempt to avoid multiple EA/EIRs for the covered projects (e.g., 14 Cal. Code Regs. § 15168(b)(3), (c)(5)), but without adequate project-specific information to complete CEQA or NEPA review. This level of review is more appropriately provided for a programmatic EA/EIR, which may lack site-specific and discrete project details. (14 Cal Code Regs § 15168(b)(4); *In re Bay-Delta Programmatic Envt'l Impact Report Coordinated Proceedings* (2008) 43 Cal.4th 1143.)

A "finite project description is indispensable to an informative, legally adequate EIR." *County of Inyo v. City of Los Angeles* (1977) 71 Cal.App.3d 185, 192. Without a complete and accurate description of the project and all of its components, an accurate environmental analysis is not possible. *See*, *e.g.*, *Santiago County Water Dist. v. County of Orange* (1981) 118 Cal.App.3d 818, 829; *Sierra Club v. City of Orange* (2008) 163 Cal.App.4th 523, 533; *City of Santee v. County of San Diego* (1989)214 Cal.App.3d 1438, 1450; *Blue Mountains Biodiversity Project v. United States Forest Service*, 161 F.3d 1208, 1215 (9th Cir. 2008). Similarly, without a clearly stated NEPA purpose and need, a reasonable range of alternatives to achieve such purpose cannot be evaluated. (40 C.F.R. § 1502.13.)

A. The Amounts, Location, and Timing of Dredging Projects and Placement Sites are Entirely Uncertain.

The proposed project purportedly seeks to continue the existing maintenance dredging program through the San Francisco Bay Area. However, the EA/EIR frequently asserts that higher volumes of sediment may be dredged in the future than has been dredged in the past. In fact, the EA/EIR provides no upper limits to future dredge amounts, no estimates of increased dredge volumes, and no criteria to assess when or if an increase in dredge volumes may occur.

Table ES-2 illustrates this open-ended project description, providing a "range of volume per dredge episode" that is quite large; for example, ranging from 11,000-631,000 CY for Richmond Inner Harbor, 78,000-613,000 CY for San Francisco Harbor, and 122,000-1,055,000 for Oakland Inner and Outer

Harbors. (EA/EIR ES-6 to ES-7.) As if these ranges were not broad enough, Table ES-5 goes on to state that for the Napa River, Petaluma River, San Rafael Creek, Oakland Inner and Outer Harbors, and San Leandro Marina, that "future dredge volumes could be greater."

Compounding upon this uncertainty, the EA/EIR offers three to four alternative placement sites for each dredge project, some of which are vaguely described as "Other In-Bay Site," or "Upland Beneficial Reuse." (EA/EIR Table ES-2.) For some projects, alternative 1 is "Other In-Bay," and alternative 2 is "Upland Beneficial Reuse," while for other projects, alternative 1 is "Upland Beneficial Reuse, and alternative 2 is "Other In-Bay." Similarly, the EIR states that "In some cases, dredged material may be transported outside the region for use in landfills, levee repair, or other beneficial reuse projects." (EA/EIR 1-4.) How any of these sites, whether primary or alternative, were selected, is not discussed at all. Nor does the EA/EIR provide any ability to determine how *much* fill would be placed at each site, nor how much present and total capacity each site has.

Lastly, the EA/EIR excludes from consideration a number of dredge projects and placement locations, without any explanation of how or why these activities are not encumbered by the whole of the project proposed, or embraced within the overall program. (See, e.g., EA/EIR Figure ES-1.)

B. Purpose, Need, and Future Required Permits are Unclear

Throughout the EA/EIR, environmental analysis is severely circumscribed by various forms of the following logic:

> *Dredging and the associated transport and placement activities have occurred in the waters of San Francisco Bay for decades, and the No Action/No Project Alternative would involve continuation of USACE's current maintenance dredging program. . . . The No Action/No Project Alternative would allow for the same level of dredging and vessel traffic in the San Francisco Bay that currently occurs. . . . Thus, there are no expected increases in [impacts] due to the No Action/No Project Alternative.*

(EA/EIR 3.5-22.) In turn, "Implementation of the Proposed Action/Project would be very similar to the No Action/No Project Alternative," therefore resulting in no environmental impacts. Hence, the EA/EIR considers the proposed project and its continuing impacts as a foregone conclusion. Such analysis overlooks the present approval and permitting needs of the proposed project, and the associated required environmental determinations, mitigation measures, and findings. Without receiving these present and future approvals, needed now, it is simply untrue that the historic and ongoing project impacts would continue into the future.

Unfortunately, however, nowhere does the EA/EIR clearly lay out its reasons for existing. The EA/EIR states that:

> *This document is intended to fulfill USACE's NEPA compliance requirements for maintenance dredging of federal navigation channels it maintains in San Francisco Bay*

> *for the federal fiscal years 2015 through 2024. This document is also intended to fulfill the Regional Water Board's CEQA compliance requirements for issuance of a 10-year WQC to USACE.*

(EA/EIR ES-1.) NEPA compliance alone does not provide a complete statement of project purpose under NEPA, but rather, a circular one. Given the EA/EIR's repeated reliance on the project as "ongoing" and even historic, greater clarity is required to understand which historic or ongoing project approvals have expired or are expiring, and what subsequent project approvals will be required.

Again, the environmental document should more appropriately be styled as a programmatic EA/EIR, given the repeated uncertainty regarding future, site-specific conditions and timing.

IV. Greenhouse Gas Emissions are Inadequately Reviewed

The EA/EIR reasons that the proposed project would not result in any net increase in GHG emissions since the proposed project would generally continue ongoing activities. (EA/EIR 3.5-22 to 3.5-23.) However, as noted above, the EA/EIR leave room for substantial increases in dredging in future years under the proposed program, and these impacts above baseline activities have not been accounted for. In addition, to the extent the maximum permitted volumes were not reached each year historically at the DODS, but may be permitted to do so now through the proposed project, the additional air emissions including GHG impacts from shipping to DODS must be evaluated in this document.

V. Conclusion

In summary, we ask that the environmental review document be revised and recirculated to provide an appropriate level of review and protection of sediment resources in the region. More information is required to determine how and whether the proposed project would comply with ocean disposal criteria, and more information is required to understand what feasible mitigation measures and project alternatives could allow for a higher degree of beneficial reuse of suitable dredge materials. Finally, without project-level details provided regarding the timing, amount, and location of future dredge projects and associated placement of dredge material, the EA/EIR should be revised to provide for programmatic, rather than project-level review, with subsequent environmental review documents that may tier from the programmatic review, to be prepared when site-specific information is available.

Sincerely,

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Staff Scientist, San Francisco Baykeeper

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Exhibit B

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Linking Human Impacts within an Estuary to Ebb-tidal Delta Evolution

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ABSTRACT

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San Francisco Bay, California, USA is among the most anthropogenically altered estuaries in the entire United States, but the impact on sediment transport to the coastal ocean has not been quantified. Analysis of four historic bathymetric surveys has revealed large changes to the morphology of the San Francisco Bar, an ebb-tidal delta at the mouth of the San Francisco Bay. From 1873 to 2005 the bar eroded an average of 80 cm, which equates to a total volume loss of $100 \pm 65 \times 10^6$ m^3 of sediment. Comparison of the surveys indicates the entire ebb delta has contracted radially while its crest has moved landward an average of 1 km. Compilation of historic records reveals that 130×10^6 m^3 of sediment has been permanently removed from the San Francisco Bay and adjacent coastal ocean. Constriction of the bar is hypothesized to be from a decrease in sediment supply from San Francisco Bay, a reduction in the tidal prism of the estuary, and/or a reduction in the input of hydraulic mining debris. Changes to the morphology of the San Francisco Bar have likely altered wave refraction and focusing patterns on adjacent beaches and may be a factor in persistent beach erosion occurring in the area.

ADITIONAL INDEX WORDS: *San Francisco Bay, San Francisco Bar, long-term changes, bathymetry, sedimentation, erosion*

INTRODUCTION

Anthropogenic activities within coastal estuaries may affect sediment delivery to the coastal ocean. Because beaches and nearshore bars are supplied in part from this material, activities that alter sediment delivery are important to quantify. Ocean Beach, California, USA (Fig. 1) is located near the mouth of the San Francisco Bay estuary and has been eroding along its southern reach for decades. Modeling results and bedform analysis for the area show distinct pathways for the seaward transport of bed load and suspended load out of San Francisco Bay (BARNARD et al., in press). Sediment management practices inside the bay, therefore, at least partly influence the amount of sediment transported to the coastal ocean.

San Francisco Bay is one the largest estuaries in the United States and has been continuously altered by a range of activities, including influx by hydraulic mining debris, mining of fill for bay development, dredging of harbors and waterways, and mining of sand and gravel for use as construction aggregate The bay is connected to the Pacific Ocean by the narrow Golden Gate Inlet, where during peak ebb flow depth-averaged currents can exceed 2 5 m/s (BARNARD et al., 2007). After the ebb jet emerges from the inlet throat the velocity decreases and coarse sediment is dropped This sediment, and sediment supplied by littoral drift, accumulates to form the San Francisco Bar, a 100 km^2 ebb-tidal delta (Fig 1). The bar is shaped by tidal currents and waves and exerts a strong influence on wave refraction and focusing patterns on adjacent beaches (BARNARD et al., 2007) This in turn, impacts beach morphology, a critical issue at Ocean Beach where erosion threatens valuable infrastructure.

The objective of this study is to quantify the impact of anthropogenic activities within San Francisco Bay on the amount of sediment delivered to the coastal ocean. To assess this impact, dredging and mining records were compiled and historic bathymetric models of the San Francisco Bar were generated. This study builds on previous work in the area by GILBERT (1917), MOFFATT AND NICHOL (1995), BATTALIO AND TRIVEDI (1996), BARNARD et al. (2007), JAFFE et al. (2007), FREGOSO et al. (2008) and others, but is the most comprehensive study on long-term bathymetric change of the San Francisco Bar to date.

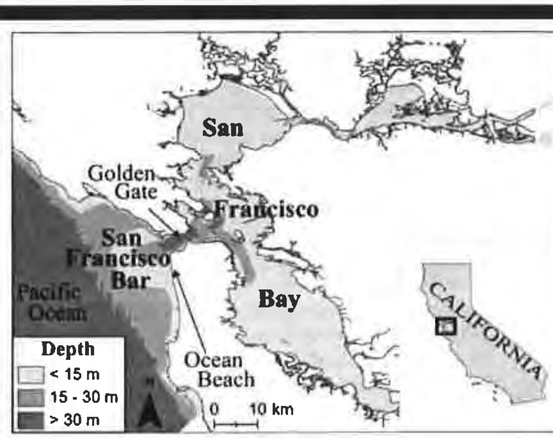

Figure 1. Location of study area near the San Francisco Bay estuary, California.

METHODS

Volumes for historic dredging and borrow pit mining events in San Francisco Bay were compiled by a thorough literature search (e.g. MARKWART, 1973, US ARMY CORPS OF ENGINEERS, 1975, SCHEFFAUER, 1954). Volumes reported represent only those sediments that were permanently removed from the system either through beneficial reuse, disposal on land, or disposal in the deep ocean. Sand mining volumes were collected from annual reports submitted to the Bay Conservation and Development Commission.

Sounding data from four historic bathymetric surveys were used to create continuous bathymetric grids of the San Francisco Bar. Creation of accurate surface grids involved several steps. For the 1873 and 1900 grids, soundings were digitized from hydrographic sheets obtained from the National Ocean Service (NOS). Sounding data were then registered to a common horizontal datum using latitude/longitude graticules. For the 1956 and 2005 grids, registered soundings were obtained directly from NOS and the California State University, Monterey Bay Sea Floor Mapping Lab, respectively. Bathymetric TIN grids with a horizontal resolution of 25 meters were generated for each survey. Grids were adjusted to a common vertical datum (NAVD88) to account for changes in sea-level rise (i.e. tidal epoch and tidal datum) and differenced to create bathymetric change grids. To improve comparability of all surveys, bathymetric change maps were limited to a 125 km^2 area that contained data for all four surveys. Net sediment volume change for each survey period was calculated by multiplying the average depth change between surveys by the surface area of the grid. Crest location was determined for each survey by extracting the shallowest depth along 40 transects cast roughly perpendicular to the crest.

Error and Uncertainty Analysis

The total bathymetric grid uncertainty is a combination of potential errors and uncertainties, including sounding measurement uncertainty, vertical tidal inconsistencies, and gridding bias errors. While some uncertainties/errors can be assessed with high precision, others can only be estimated. It is noted that the total grid error is believed to be far less than the grid uncertainty. For example, grid bias was calculated by comparing every sounding to its associated grid value and finding the mean difference. Grid bias was small (0.1 cm to 0.52 cm) and is included in the uncertainty calculation even though it was removed from the grids. On the other hand, measurement uncertainties of individual soundings from the 1873 and 1900 surveys can only be estimated. An average uncertainty can be estimated by using the error criteria employed during surveying. In the early surveys sounding error was determined in the field by comparing separate measurements at trackline crossings and was not to exceed 3% of the water depth (SCHALOWITZ, 1964). Visual observations of trackline crossings and observations of the pinching out of profiles from different years on the inner continental shelf indicate sounding error is not systematic. The same long-term morphological trends were also found in Central San Francisco Bay by FREGOSO et al. (2008) and provide further support for sounding error being non-systematic. Due to the complexity of error assessment, uncertainties could only be estimated. As a conservative estimate, $\pm$0.4 m was applied for the 1873 and 1900 surveys, $\pm$0.2 m for 1956, and $\pm$0.12 m for 2005. Volume change uncertainties were calculated by multiplying the sum of uncertainties of both surveys by the surface area of the grid. For example, the volume change uncertainty from 1956 and 2005 is $\pm$0.32 m (0.2 m + 0.12 m) times the surface area of the grid. These estimates assume a systematic error throughout the surveys, but there is no evidence that the error is this large for any of the volume calculations. Future research will explore options for reducing these uncertainties.

RESULTS

Anthropogenic impacts

The greatest single impact to the San Francisco Bay floor was the influx of hydraulic mining debris. GILBERT (1917) estimated that approximately 1.15 x 10^9 m^3 of sediment was transported to the bay from 1849 to 1909. This pulse of sediment, in tandem with widespread development and loss of wetlands, caused a ~30% reduction in the tidal prism (BARNARD et al., 2007).

Since 1900 a minimum of 130 million m^3 (Mcm) of sediment has been permanently removed from the San Francisco Bay and adjacent coastal ocean through borrow pit mining (27 Mcm), aggregate mining (26 Mcm), and dredging (77 Mcm) (Fig. 2). This is a minimum estimate because not all records have been compiled (missing 1976-1996 dredge records and borrow pit mining records for the San Francisco waterfront, Alameda Air Base, BART tunnel, and Oakland Airport) and some records are incomplete. A majority of the sediment was removed from Central Bay (52%), with lesser amounts removed from the North Bay (28%), San Francisco Bar (18%), and South Bay (2%). The largest single event was the removal of 22 Mcm of sand from Central San Francisco Bay for the building of Treasure Island from 1936-1938 (SCHEFFAUER, 1954).

Historical bathymetric change to the San Francisco Bar

The San Francisco Bar has experienced periods of erosion and deposition since the first detailed survey in 1873. From 1873 to

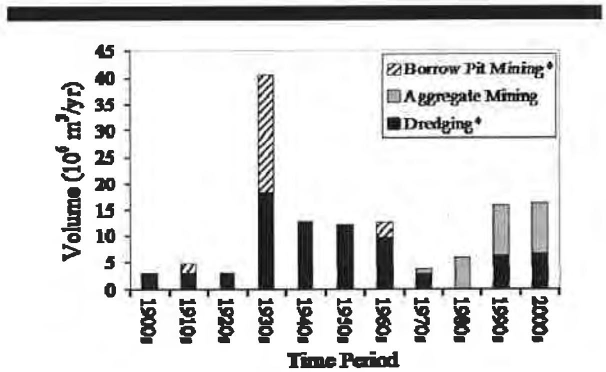

Figure 2. Volume of sediment permanently removed from the San Francisco Bay and coastal ocean. *incomplete data

1900 a net volume of 78 $\pm$ 124 Mcm was eroded across the bar, with an average depth change of -0.63 m (Fig. 3). During this time, erosion occurred along the entire length of the crest and within the inner most portion of the bar. From 1900 to 1956 a net volume of 52 $\pm$ 75 Mcm of sediment was deposited on the bar, with an average depth change of +0.42 m (Fig. 3). Significant changes include accretion landward of the crest, initiation of channel dredging, and migration of the crest landward. Comparison of the 1956 and 2005 surveys reveals net erosion of 75 $\pm$ 40 Mcm of sediment, with an average depth change of -0.60 m (Fig. 3). During this period erosion of the crest was widespread with additional erosion in the ship channel from modified

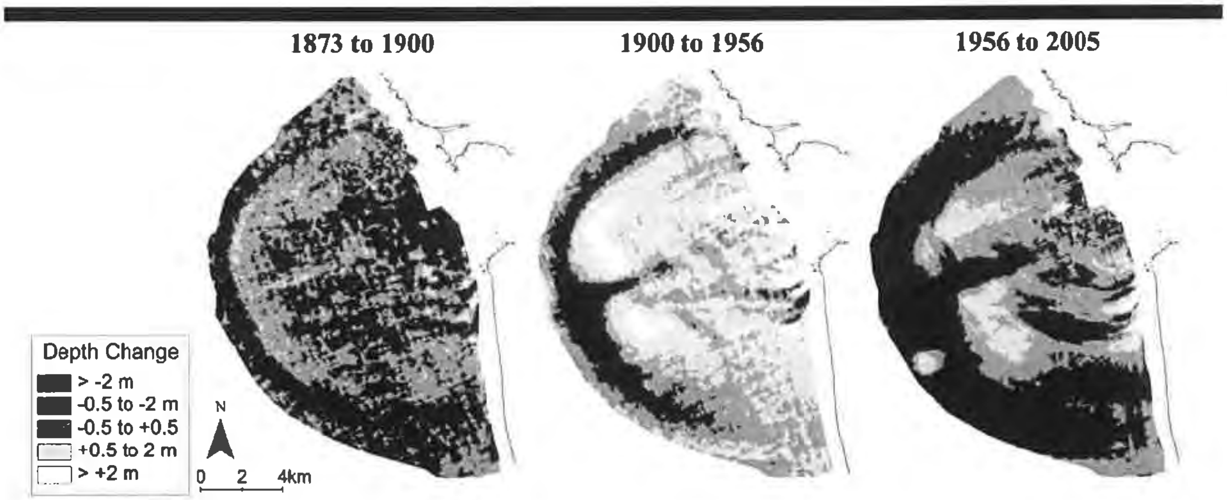

Figure 3. Bathymetric change maps of the San Francisco Bar from 1873 - 2005.

dredging practices to deepen and widen the channel. A distinct accretionary mound can also be seen south of the ship channel as a result of dredge disposal in this location since 1973. Accretion is also evident along the peripheral flood channels and may represent a decrease in flow through these channels as a result of increased hydraulic efficiency of the main channel due to dredging (HANES AND BARNARD, 2007). Comparison of the 1873 and 2005 surveys reveals net erosion of 100 ± 65 Mcm of sediment, with an

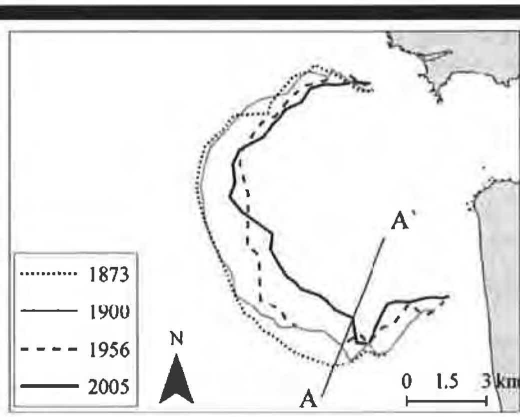

Figure 4. Location of the crest of the San Francisco Bar from 1873 – 2005.

average increase in depth of -0.8 m.

Consistent across all surveys is a landward migration of the crest through time (Fig. 4). Cross sections through the ebb delta demonstrate continued radial shrinking throughout the study period despite overall accretion between 1900 and 1956 (Fig. 5). In the northern and central sections of the bar, where the crest is narrow and well defined, the crest has moved landward an average of ~1 km since 1873, with a maximum landward movement of ~1.6 km.

DISCUSSION

The general shape of any ebb-tidal bar is determined by a balance between tidal currents, waves, and the amount of sediment supplied (HAYES, 1980). Previous studies indicate any modification in the factor(s) listed above can produce significant morphological response (see ELIAS AND SPEK, 2006; FAN et al., 2006; SYVITSKI AND SAITO, 2007). Results presented here reveal large changes in the morphology of the San Francisco Bar and suggest a change in the forcing factors or boundary conditions. Although waves are highly variable over short timescales, it is assumed that the average wave strength remained constant over the 132 years encompassed in this study. Continued radial shrinking of the bar would result from a decrease in sediment supply, reduction in the tidal prism of the estuary, and/or a reduction in the input of hydraulic mining material.

Damming of rivers that drain into the San Francisco Bay and dredging, borrow pit mining, and aggregate mining within the estuary have changed sediment dynamics from its natural state. WRIGHT AND SCHOELLHAMER (2004) found that the three largest reservoirs in the watershed have impounded over 60 Mcm of sediment, while results from this study indicate a minimum of 130 Mcm of sediment has been removed from the estuary. It is noted that the specific median grain sizes of the trapped or

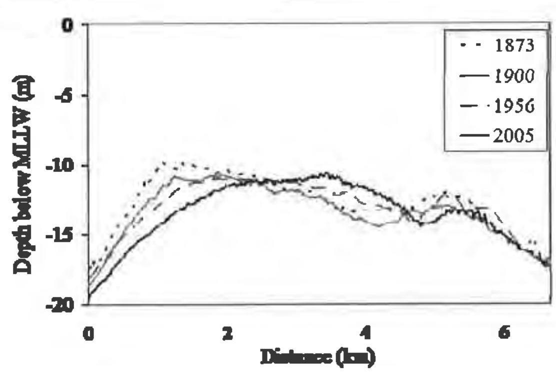

Figure 5. Profile of San Francisco Bar along line A-A' (Fig 4) from 1873 – 2005.

removed sediments are unknown, so it is impossible to know what fraction would affect morphology of the ebb delta (median grain size 0.19 mm) (BARNARD et al., 2007). However, from sand mining reports and sampling of the bay floor in areas formerly used for dredging and borrow pit mining, we know that each of these activities did utilize sediment that is compatible with grain sizes on the bar, so each are important to consider.

The second hypothesis to explain contraction of the ebb delta is a change in the tidal prism of the San Francisco Bay. A reduction in the tidal prism of the estuary due to development, sedimentation, and infilling of marshes has been recorded by previous studies (see GILBERT,1917 and KRONE,1979). In this case, tidal currents would be reduced and the ebb-tidal delta would be shrinking to reach a new equilibrium.

The last hypothesis is a decrease in the amount of hydraulic mining debris supplied to the coast. GILBERT (1917) estimated that the effects of mining would persist for roughly 50 years after 1914, and MEADE (1982) showed that the main pulse of mining debris passed through the watershed prior to 1950. In this case, the ebb-tidal delta may still be adjusting to a large input of hydraulic mining debris and slowly evolving back to its equilibrium size. In the future we plan to investigate each of these hypotheses, all of which have likely contributed toward morphological changes of the San Francisco Bar.

CONCLUSIONS

Analysis of historical bathymetric surveys has revealed erosion of 100 $\pm$ 65 Mcm of sediment to the San Francisco Bar in the past 130 years. In addition, the bar crest has retreated landward an average of ~1 km. Changes to the morphology of the bar have likely caused changes to wave refraction and focusing patterns and altered sediment transport pathways. The erosional trend observed on the ebb-tidal delta is hypothesized to be linked to a decrease in sediment supply from San Francisco Bay, a reduction in the tidal prism of the estuary, and/or a reduced input of hydraulic mining material. Compilation of historical records indicates a minimum of 130 Mcm of sediment has been permanently removed from the system. A similar pattern of bathymetric change was found for Central San Francisco Bay by FREGOSO et al. (2008) and suggests a sediment supply link between Central Bay and the San Francisco Bar. With new management plans calling for an increase in out of bay dredge disposal, and aggregate companies lobbying to extract greater volumes, it is likely these activities will further limit the available sediment supplied to the bar. Future sediment management decisions made within San Francisco Bay should therefore consider the impacts to coastal sediment delivery.

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Exhibit C

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Anthropogenic influences on shoreline and nearshore evolution in the San Francisco Bay coastal system

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ABSTRACT

Analysis of four historical bathymetric surveys over a 132-year period has revealed significant changes to the morphology of the San Francisco Bar, an ebb-tidal delta at the mouth of San Francisco Bay estuary. From 1873 to 2005 the San Francisco Bar vertically-eroded an average of 80 cm over a 125 km^2 area, which equates to a total volume loss of 100 $\pm$ 52 million m^3 of fine- to coarse-grained sand. Comparison of the surveys indicates the entire ebb-tidal delta contracted radially, with the crest moving landward an average of 1 km. Long-term erosion of the ebb-tidal delta is hypothesized to be due to a reduction in the tidal prism of San Francisco Bay and a decrease in coastal sediment supply, both as a result of anthropogenic activities. Prior research indicates that the tidal prism of the estuary was reduced by 9% from filling, diking, and sedimentation. Compilation of historical records dating back to 1900 reveals that a minimum of 200 million m^3 of sediment has been permanently removed from the San Francisco Bay coastal system through dredging, aggregate mining, and borrow pit mining. Of this total, ~54 million m^3 of sand-sized or coarser sediment was removed from central San Francisco Bay. With grain sizes comparable to the ebb-tidal delta, and its direct connection to the bay mouth, removal of sediments from central San Francisco Bay may limit the sand supply to the delta and open coast beaches.

SWAN wave modeling illustrates that changes to the morphology of the San Francisco Bar have altered the alongshore wave energy distribution at adjacent Ocean Beach, and thus may be a significant factor in a persistent beach erosion 'hot spot' occurring in the area. Shoreline change analyses show that the sandy shoreline in the shadow of the ebb-tidal delta experienced long-term (1850s/1890s to 2002) and short-term (1960s/1980s to 2002) accretion while the adjacent sandy shoreline exposed to open-ocean waves experienced long-term and short-term erosion. Therefore, the recently observed accelerating rates of bay sediment removal, ebb-tidal delta erosion, and open coast beach erosion are all correlated temporally.

1. Introduction

Anthropogenic activities within coastal estuaries may reduce sediment delivery to the coastal ocean, decreasing sand supply to open coast beaches and ebb-tidal deltas (e.g., Davis and Barnard, 2000, 2003; Elias and van der Spek, 2006; Smith et al., 2008). Ebb-tidal deltas are bodies of sediment deposited by ebb-tidal currents on the seaward side of tidal inlets and in some locations, are huge sand reservoirs that have increasingly been examined as prospective sources of sand for beach nourishment (Cialone and Stauble, 1998). Ebb-tidal deltas can also strongly influence coastal processes in the vicinity of the tidal inlet (e.g., Davis and Fox, 1981) through partial wave sheltering of the adjacent shoreline, thereby reducing shoreline erosion (Marino and Mehta, 1987).

Studies of ebb-tidal deltas have shown that a dynamic balance between tidal energy and waves determines delta morphology, where ebb-tidal currents induce a net-offshore directed sediment flux and offshore waves induce a net-onshore directed sediment flux (Hayes, 1975; Walton and Adams, 1976). Previous studies have shown that anthropogenic activities in estuaries can have a dramatic influence on delta size and shoreline position (Barnard and Davis, 1999; Davis and Barnard, 2000; Elias and van der Spek, 2006). Analysis of a series of bathymetric surveys of an inlet and ebb-tidal delta system in the Netherlands by Elias and van der Spek (2006) demonstrated that changes to a back basin's tidal prism caused morphologic changes to the delta and erosion of the adjacent shoreline. Carter et al. (1982) and Cooper and Navas (2004) also showed that changes in ebb-tidal delta morphology altered incident

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wave energy and caused long-term shoreline change. Knowledge of the processes that impact ebb-tidal delta evolution is therefore fundamental for successful coastal management in these regions.

The morphology of San Francisco Bay's ebb-tidal delta has changed significantly over time (Gilbert, 1917; Battalio and Trivedi, 1996; Hanes and Barnard, 2007; Barnard et al., 2007), but little is known about why the delta has changed. The objectives of this study were to quantify long-term bathymetric change of the San Francisco ebb-tidal delta, assess shoreline change along the adjacent sandy shoreline, and investigate the processes driving geomorphic change in the coastal system.

2. Study area

San Francisco Bay, located at the mouth of the Sacramento-San Joaquin River system, is the largest estuary on the West Coast of the United States, draining over 40% of the state of California. The estuary consists of three sub-embayments – North Bay (San Pablo and Suisun Bays), Central Bay, and South Bay (Fig. 1). San Francisco Bay is an urbanized estuary, and with the surrounding area home to over 7 million people (United States Census Bureau, 2009), is widely considered to be the estuary most impacted by human activities in the United States (Nichols et al., 1986).

San Francisco Bay is connected to the Pacific Ocean by the narrow Golden Gate inlet (Fig. 1). The large surface area of the bay and diurnal tidal range of 1.78 m creates an annual maximum tidal prism of $\sim$2 billion m^3 ($\sim$2 trillion liters), which causes peak ebb flow depth-averaged currents in the inlet to exceed 2.5 m/s (Barnard et al., 2007). After the ebb jet emerges from the inlet throat, the velocity decreases and coarse sediment is deposited. The tidally transported sediment, and sediment supplied by littoral drift, accumulates to form the $\sim$150 km^2 ebb-tidal delta, the San Francisco Bar (Fig. 1).

The San Francisco Bar is shaped by tidal currents and waves, which regularly exceed 6 m in height on the continental shelf during major winter storms (Coastal Data Information Program [CDIP], 2010). The ebb-tidal delta has a horse-shoe shape with a dredged shipping channel across its central crest and two peripheral flood channels adjacent to the coast. Grain size varies across the delta, ranging from coarse sand and gravel near the inlet entrance to fine sand on the outer reaches. Numerical modeling results indicate that the ebb-tidal delta plays an important role in dissipating wave energy through wave refraction, and in some cases can reduce wave heights by 50% (Barnard et al., 2007). Wave refraction and focusing directly impact beach morphology at adjacent Ocean Beach.

Ocean Beach is a 6.5 km long sandy beach located just to the south of the entrance to San Francisco Bay (Fig. 1). The proximity to the inlet creates strong alongshore tidal currents that can exceed 1 m/s (Barnard et al., 2007). This area is also exposed to high wave energy with a mean annual offshore significant wave height of 2.4 m, but winter offshore storm heights can exceed 9 m (CDIP, 2010). Since 1997 there has been a trend of shoreline accretion in the northern and central portions of Ocean Beach and shoreline erosion in the southern reach (Barnard et al., 2007). The southern reach of the beach has been eroding for decades (Domurat et al., 1979; Hapke et al., 2006; Hansen and Barnard, 2010), with a recent mean shoreline retreat of 15.1 m since 1997 (Barnard et al., 2007). Chronic erosion in this location has claimed portions of two parking lots and badly damaged a major roadway.

3. Methods

3.1. San Francisco ebb-tidal delta bathymetric change

Sounding data from four hydrographic surveys of the San Francisco ebb-tidal delta were used to analyze long-term bathymetric change: 1873, 1900, 1956 and 2005. For the 1873 and 1900 surveys, soundings were digitized from hydrographic sheets obtained from the National Ocean Service (NOS) and registered to a common horizontal datum using graticules and triangulation stations. For the 1956 survey, registered soundings were obtained directly from NOS. The 2005 multibeam bathymetry data set was received in registered, grid format from the surveyors at the Sea Floor Mapping Lab at California State University, Monterey Bay.

Continuous bathymetric surface representations of the 1873, 1900, and 1956 surveys were created using triangulated irregular network surfaces that were converted to raster grids with a horizontal resolution of 25 m. For all years, grids were compared to original sounding data to check for problem areas. All historic grids were adjusted from mean lower low water (MLLW) to a common

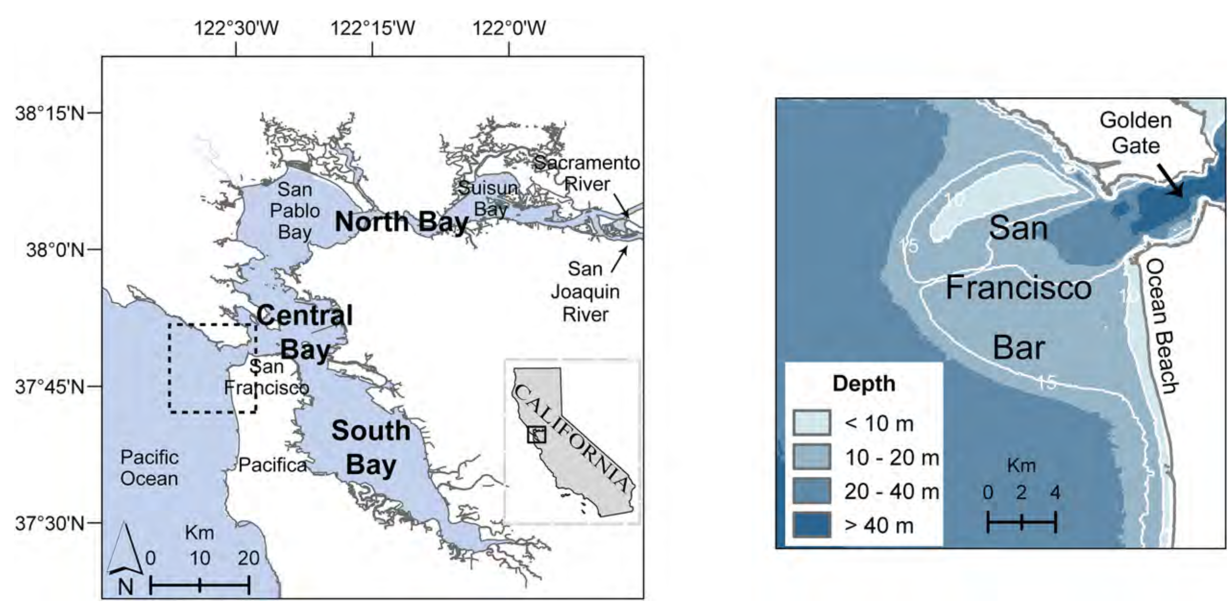

Fig. 1. Location of the San Francisco ebb-tidal delta at the mouth of the San Francisco Estuary, California. Dashed box indicates study focus area. Bathymetric contours from 2005 in meters.

Table 1
Bathymetric grid uncertainties (m) for historic surveys.

Uncertainties (m)	1873	1900	1956
Gridding interpolation	0.03	0.01	0.01
Sounding uncertainty	0.40	0.21	0.21
MLLW uncertainty	0.09	−0.09	–
Total Grid Uncertainty (m)	0.41	0.23	0.21

vertical datum (NAVD88) to account for sea-level rise and tidal staff variations through time and differenced to create bathymetric change grids. Bathymetric change grids were used to calculate volume change for each survey period. Ebb-tidal delta crest location was determined by extracting the shallowest depth along 40 transects cast roughly perpendicular to the crest.

3.2. Bathymetric change error and uncertainty analysis

The total bathymetric grid uncertainty is a combination of potential errors and uncertainties, including gridding interpolation error, sounding measurement uncertainty, and MLLW datum uncertainty (Table 1). The total grid error (i.e., systematic error) is believed to be far less than the grid uncertainty of an individual cell. Gridding interpolation error (error that results from interpolating between point sounding data) was calculated by removing 10% of the sounding data and gridding the remaining data. Every sounding removed was compared to its associated grid cell value and the average difference for all of the removed data represents the gridding interpolation error. Gridding interpolation error was small and was removed from the grids, but to be conservative was retained in the uncertainty calculation.

Measurement uncertainty for the historic surveys can only be estimated based upon the error criteria employed during surveying. During the historic surveys sounding error was determined in the field by comparing separate measurements at trackline crossings and was not to exceed 3% of the water depth (Shalowitz, 1964). Comparison of soundings at trackline crossings and observations of similar depths offshore of the delta from different surveys indicate that systematic sounding error was not significant (i.e., $<<$individual cell uncertainty). Sounding uncertainty was conservatively estimated for each survey by multiplying the maximum error permitted at the time of surveying by the mean survey depth.

The 1873 and 1900 surveys also have MLLW datum uncertainties due to the MLLW datum chosen during surveying. Unlike the 1956 and 2005 surveys, where the MLLW datum was calculated over a 19-year tidal epoch, the earlier surveys used a 3-month average of MLLW. To assess the uncertainty that arises from using a shorter time period, a 19-year average MLLW was calculated for each survey using historical tide gauge records and compared to the survey MLLW.

A total uncertainty for each historical survey was estimated by taking the square root of the sum of the squares of the gridding interpolation error, sounding uncertainty, and MLLW uncertainty (Table 1). An uncertainty of $\pm$0.12 m was assigned to the 2005 data set, which was provided by the surveyors based on robust harbor testing and evaluation of trackline overlaps. Volume change uncertainties were calculated by multiplying the square root of the sum of the squares of total survey uncertainties by the surface area of the grid. These estimates are very conservative and assume a systematic error throughout the surveys, even though there was no evidence that the error was this large for any of the volume calculations. However, because it was not possible to provide a more quantitative assessment of systemic survey error, the conservative approach of simply applying the grid cell uncertainty to the entire survey was chosen.

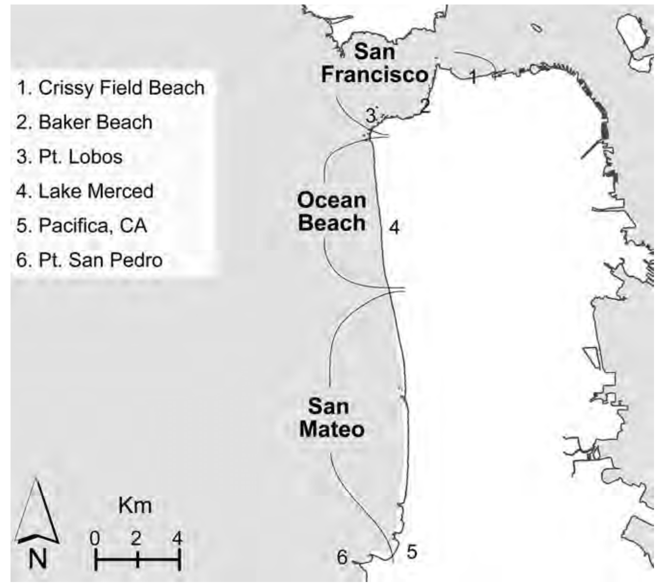

Fig. 2. Index map showing the three shoreline change analysis regions and various locations mentioned in the text.

3.3. SWAN wave modeling

The SWAN wave model (Holthuijsen et al., 1993; Delft3D, 2007) was run in a stand-alone, stationary mode with grids and model parameters from Eshleman et al. (2007). Three nested grids with consecutively finer resolutions (500 m, 200 m, and 100 m) were used. The bathymetry files were interpolated onto the wave grids in the following order of importance: ebb-tidal delta bathymetry from the 2005 multibeam survey (Kvitek, 2010), modern nearshore bathymetry collected using Personal Watercraft from 2004 to 2006 along Ocean Beach (Barnard et al., 2007) used to fill in gaps in shallow water areas (for methods see Ruggiero et al., 2005), and bathymetry data compiled by the National Marine Sanctuary Program in 2003 for areas offshore of the ebb-tidal delta. The model was run with parameterized wave forcing and did not include wind, tidal currents, or wave–wave interactions. Model runs were repeated using the ebb-tidal delta bathymetric data sets and output maps of significant wave heights were differenced to analyze historical changes in wave height.

3.4. Sediment removal

The volume of sediment permanently removed from the San Francisco Bay and the San Francisco Bar (i.e., the San Francisco Bay coastal system) through dredging and borrow pit mining was quantified by a literature search (Markwart, 1915; Scheffauer, 1954; United States Army Corps of Engineers, 1975; Ogden Beeman and Associates and Ray Krone and Associates, 1992). Hardcopy dredging files were not reviewed for this research, so dredging results are minimum values. Dredging volumes reported here represent only those sediments that were disposed of outside the bay. These volumes include dredge spoils placed on land, in the deep ocean, or those used in beneficial reuse projects. Records of borrow pit mining events are scarce and the volume of material removed was often not reported, so borrow pit mining results are also minimum values. Aggregate mining volumes were collected from reports submitted by aggregate mining companies to the San Francisco Bay Conservation and Development Commission (BCDC) and California State Lands Commission. Aggregate mining has occurred in the San Francisco Bay–Delta estuary since the 1930s, however records prior to the establishment of BCDC in 1974 are incomplete and unreliable and were not incorporated into this research.

3.5. Shoreline change

Long-term (1850s/1890s to 2002) and short-term (1960s/1980s to 2002) shoreline changes were evaluated from Crissy Field Beach to Point San Pedro (~30 km) (Fig. 2). To assess shoreline change along sections of coast that experience similar wave and tidal energy, the coastline was broken into 3 separate regions – San Francisco, Ocean Beach, and San Mateo (Fig. 2). Existing shorelines were acquired digitally from the United States Geological Survey National Assessment of Shoreline Change (Hapke et al., 2006) and the National Oceanic and Atmospheric Administration Shoreline Data Explorer (NOAA, 2009) and are originally from topographic sheets (T-sheet), digital raster graphics (DRG), and light detection and ranging (lidar) data sets. In addition, aerial imagery (1983) and lidar data (1997, 1998, and 2002) were used to supplement the existing shorelines.

To compare historic high water line (HWL) shorelines and modern mean high water (MHW) shorelines it was necessary to apply a bias correction (Ruggiero et al., 2003; Hapke et al., 2006; Moore et al., 2006). Previous studies have found large horizontal offsets of up to 50 m (Ruggiero et al., 2003) between these shoreline indicators. The bias correction was adapted from Hapke et al. (2006) and was applied to all historic HWL shorelines. Shoreline change rates were calculated for the sandy shoreline at shore perpendicular transects spaced 50 m apart and averaged for each region using the Digital Shoreline Assessment System (Thieler et al., 2005). Short-term shoreline change rates were calculated at each transect using the endpoint method comparing the 1960s/1980s and 2002 shoreline positions. Long-term rates of shoreline change were calculated using linear regression applied to all shorelines from the earliest (1850s/1890s) to 2002.

3.6. Shoreline change errors and uncertainty analysis

The total error for the short-term shoreline change rate was calculated by taking the square root of the sum of the squares of T-sheet/DRG error, georeferencing error, digitizing error, and shoreline position error (Hapke et al., 2006) (Table 2). T-sheet/DRG error reflects errors present in the original surveying methods. Georeferencing error applies to shorelines derived from T-sheets, DRGs, and aerial photographs and reflects the maximum root mean square error found during the georeferencing procedure. Digitizing error reflects the ability of the digitizer to accurately digitize the shoreline and was taken as the maximum error specified in previous studies (Anders and Byrnes, 1991; Crowell et al., 1991; Moore, 2000). Shoreline position error is the average bias uncertainty for historical shorelines (Hapke et al., 2006) and the maximum error associated with the derivation of a lidar shoreline for lidar data (Stockdon et al., 2002).

Separate total position errors were calculated for each shoreline (Table 2). Short-term, annualized uncertainty was calculated for each region by taking the square root of the sum of the squares of the older shoreline error and recent shoreline error and dividing by the total time between shoreline dates (Hapke et al., 2006). Long-term shoreline change rate uncertainty was based on the 90% confidence interval of the linear regression for each transect and the uncertainty of the proxy-datum offset (see Hapke et al., 2006 for a more thorough discussion).

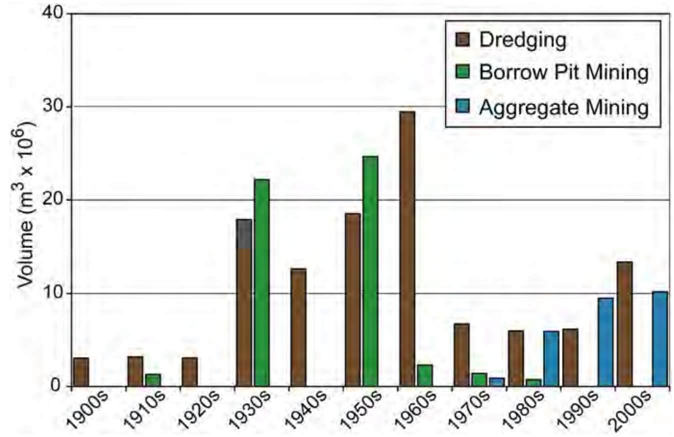

Fig. 3. Volume of documented sediment removed from the San Francisco Bay coastal system through dredging, borrow pit mining, and aggregate mining from 1900 to 2008.

4. Results

4.1. Sediment removal

Between 1900 and 2008 a minimum of 200 million m^3 (Mcm) of sediment were removed from the San Francisco Bay coastal system through dredging (120 Mcm), borrow pit mining (54 Mcm), and aggregate mining (26 Mcm) (Fig. 3). As stated prior, the dredging total represents events where sediment was removed from the San Francisco Bay coastal system, and does not include projects where sediment was simply relocated within the system. The total of 200 Mcm is a minimum estimate because not all records have been compiled (missing 1990–1996 dredge records and likely many additional borrow pit, aggregate mining, and dredging records). A majority of the sediment from 1900 to 1990 (missing spatial data from 1997 to 2008) was removed from Central Bay (113 Mcm), with lesser amounts removed from the North Bay (41 Mcm), San Francisco ebb-tidal delta (21 Mcm), and South Bay (3 Mcm). Grain sizes are unknown for much of the sediment, but where data were recorded 75 Mcm were sediment that was fine sand or coarser.

4.2. Historical bathymetric change to the San Francisco ebb-tidal delta

4.2.1. Change from 1873 to 1900

In 1873 the San Francisco ebb-tidal delta had a continuous crest, with a broad outer region where depths ranged from 10 to 11 m

Table 2
Maximum estimated errors (m) for individual shorelines.

Errors (m)	1857	1877	1866_1899	1929	1941	1950s	1963	1977	1983	1997	2002
Shoreline extent[a]	SF	SF	OB, SM	OB, SM	SF	OB, SM	SM	SF	SF, OB, SM	SF, OB, SM	SF, OB, SM
T-sheet/DRG position	10	10	10	10	10	15	3	3	–	–	–
Georeferencing	15	8.5	4	4	4	4	6.7	3.5	6	–	–
Digitizing	1	1	1	1	5	1	5	5	5	–	–
Shoreline position uncertainty	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	1.5	1.5
Total position error (m)	20	16	14	14	15	18	12	11	12	1.5	1.5

[a] SF = San Francisco, OB = Ocean Beach, SM = San Mateo.

(Fig. 4a). By 1900 most of the delta was erosional and the crest had retreated landward along nearly its entire length (Figs. 4 and 5). From 1873 to 1900 a volume of 75 ± 58 Mcm eroded across the delta, with an average depth change of −0.61 m (Fig. 4b). During this period more than 85% of the delta was erosional with widespread erosion along its southern crest where it approaches the shoreline at Ocean Beach.

4.2.2. Change from 1900 to 1956

From 1900 to 1956 a volume of 51 ± 38 Mcm of sediment accreted on the ebb-tidal delta, with an average depth change of +0.42 m (Fig. 4b) (this volume change calculation includes the ship channel, which was dredged during this time period. When the channel was excluded the volume change was 18% greater). Overall,

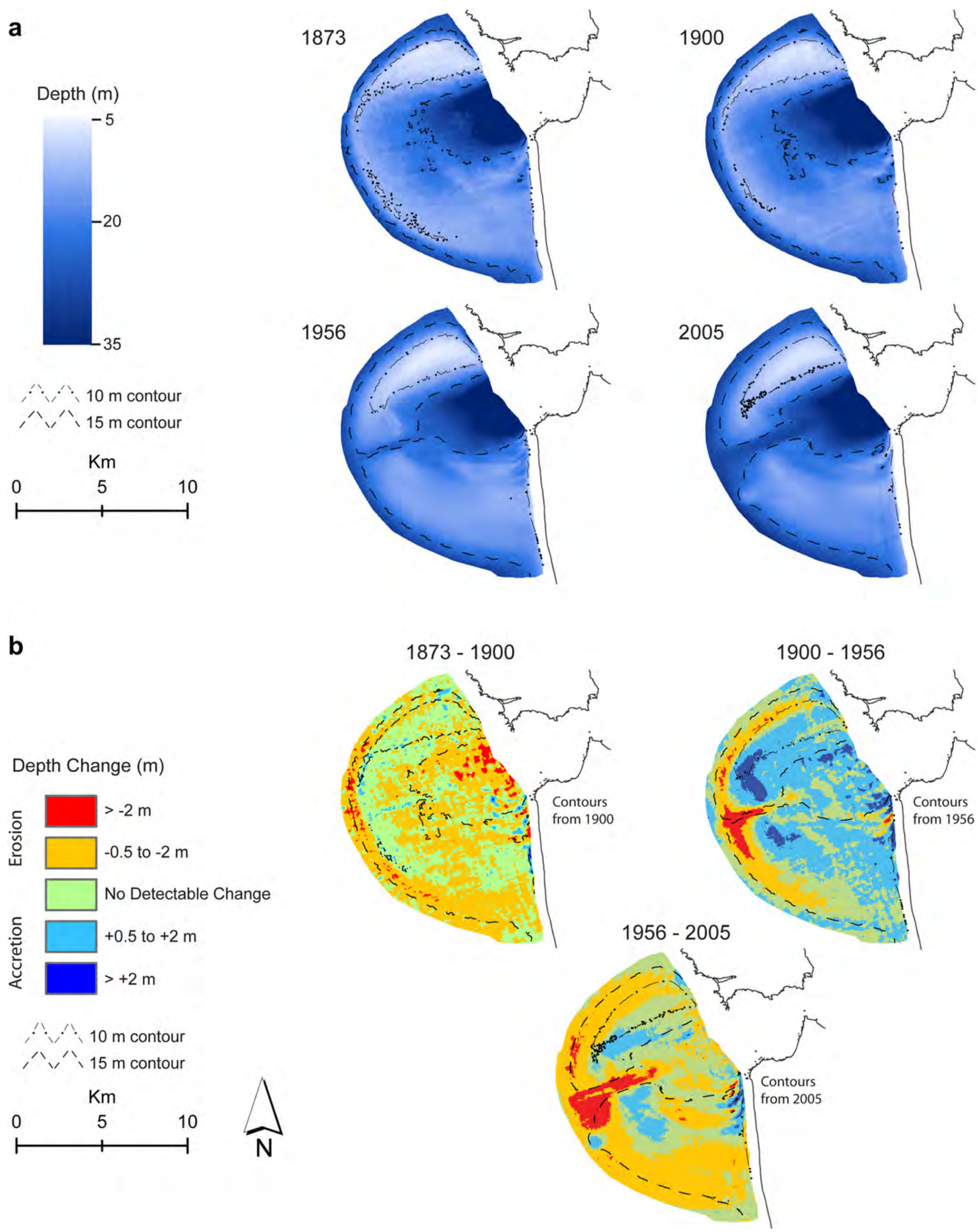

Fig. 4. (a) Bathymetry maps of the San Francisco ebb-tidal delta from 1873 to 2005 and (b) maps of bathymetric change of the ebb-tidal delta from 1873 to 2005.

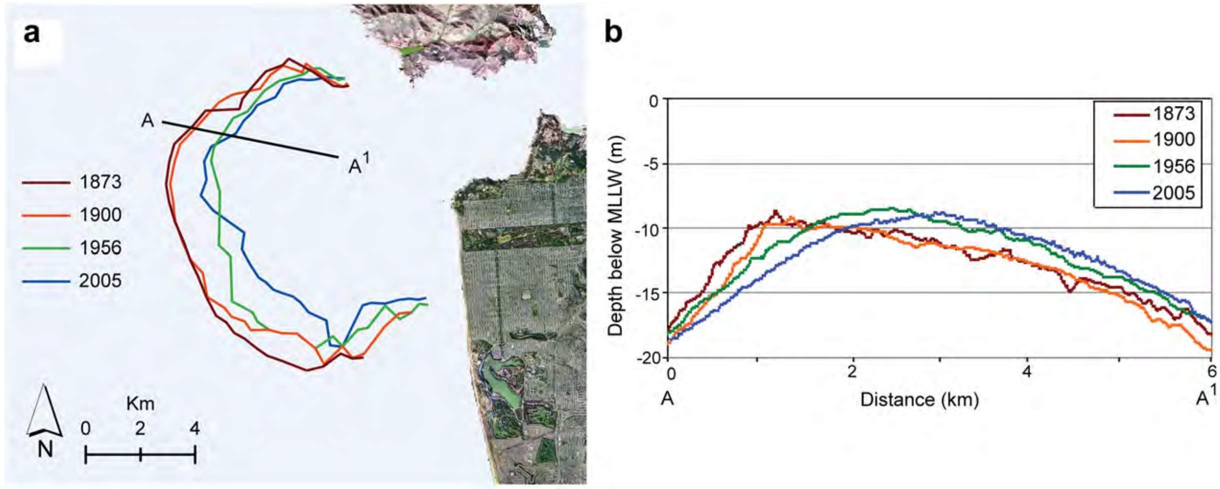

Fig. 5. (a) Location of the crest of the San Francisco ebb-tidal delta from 1873 to 2005 and (b) a cross-section profile through the crest.

about three-quarters of the delta was accretional. Accretion was most pronounced in the central part of the delta landward of the crest and within the flood channel adjacent to Ocean Beach. The primary erosional areas were along the length of the crest and within the ship channel where dredging began in 1931. Although the delta experienced net accretion from 1900 to 1956, the crest continued to contract radially with a maximum crest retreat of 1.6 km (Fig. 5).

4.2.3. Change from 1956 to 2005

Comparison of the 1956 and 2005 surveys reveals net erosion of 76 ± 30 Mcm of sediment, with an average depth change of −0.45 m (Fig. 4b) (volume change is 20% less if the dredged ship channel is excluded). More than 75% of the delta was erosional with major sediment loss around the crest and within the ship channel due to modified dredging practices to deepen and widen the channel (Fig. 4b). A distinct accretionary mound can be seen south of the ship channel as a result of dredge disposal occurring in this location since 1971. Accretion is also evident along the flood channel offshore Ocean Beach and may represent a decrease in flow through this channel as a result of increased hydraulic efficiency of the main channel due to dredging (Hanes and Barnard, 2007). Similar to other time periods, the crest of the delta retreated landward from 1956 to 2005 (Fig. 5).

4.3. SWAN numerical wave modeling

Results from SWAN wave modeling simulations illustrate that observed long-term changes to the morphology of the San Francisco ebb-tidal delta have altered wave heights and wave focusing. Changes in modeled significant wave heights from 1873 to 2005 (with parameterized forcing of significant wave height (H_s) = 3 m, peak period (T_p) = 12 s, and mean direction (D_p) = 300°, which is characteristic of a majority of waves seen in this region) are shown in Fig. 6a. Modeled results show an increase in wave heights of up to 0.6 m in the northern part of the delta landward of the crest and in

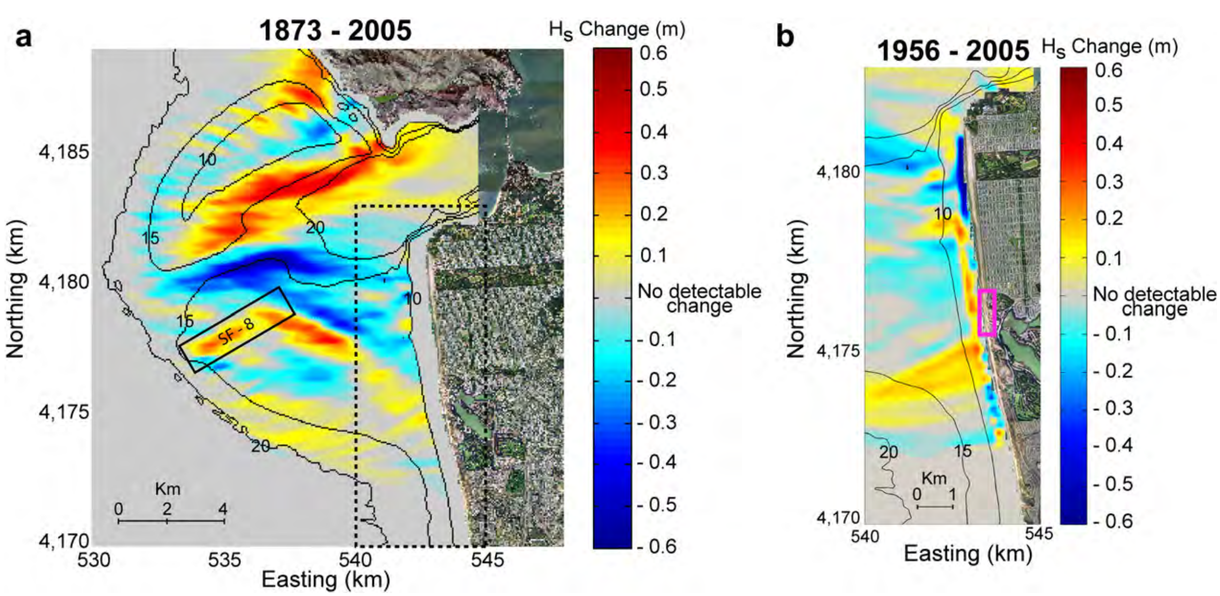

Fig. 6. Model predicted changes in significant wave height (m) (a) from 1873 to 2005 and (b) from 1956 to 2005 (model run with parameterized forcing of H_s = 3 m, T_p = 12 s, D_p = 300°). SF-8 is a federally designated dredge disposal site. Box in Fig. 6b shows location of erosion hot spot. Depth contours from 2005 in meters.

Table 3
Average shoreline change rates (m/yr).

Region	No. of transects		Average rate (m/yr)		Erosion rate (m/yr)		%Erosion (m/yr)		Accretion rate (m/yr)		%Accretion	
	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST	LT	ST
San Francisco	64	60	0.2 ± 0.2	0.6 ± 0.4	−0.1 ± 0.2	−0.2 ± 0.4	14%	13%	0.3 ± 0.2	0.7 ± 0.4	86%	87%
Ocean Beach	138	141	−0.1 ± 0.1	1.5 ± 0.6	−0.6 ± 0.1	−0.9 ± 0.6	48%	32%	0.3 ± 0.1	2.6 ± 0.6	52%	68%
San Mateo	204	184	−0.4 ± 0.1	−0.6 ± 0.3	−0.5 ± 0.1	−0.6 ± 0.3	93%	98%	0.2 ± 0.1	0.1 ± 0.3	7%	2%

Note: LT = long-term (1850–1890s to 2002), ST = short-term (1960s–1980s to 2002).

the vicinity of SF-8, a disposal area for sediments dredged from the ship channel since 1971. Wave heights have decreased up to 0.5 m in the shipping channel and along the outer crest of the delta. The same general pattern of changes in modeled significant wave heights are also seen when forced with waves originating from a more westerly approach (not shown).

Changes in significant wave heights from 1956 to 2005 along the southern portion of the ebb-tidal delta adjacent to Ocean Beach are shown in Fig. 6b. Wave heights along the shoreline generally show a decrease in the northern section of the beach and an increase in the south. This same trend is also seen when forced with typical winter storm conditions ($H_s = 7$ m, $T_p = 15$ s, $D_p = 270°$) and shows a 10% increase in wave power from 1956 to 2005 in the section of beach experiencing chronic erosion.

4.4. Shoreline change

Shoreline change rates were calculated for long-term (1850s/1890s to 2002) and short-term (1960s/1980s to 2002) time periods. The long-term shoreline change rate in the San Francisco region, averaged along 3.4 km of coastline (where sandy shoreline existed), was found to be +0.2 ± 0.2 m/yr, at the limit of error analysis, while the short-term average shoreline change rate was +0.6 ± 0.4 m/yr (Table 3). Accretion was observed along a majority of the sandy shoreline during both time periods (Fig. 7).

The long-term average shoreline change rate for the Ocean Beach region showed no significant change at −0.1 ± 0.1 m/yr, while the short-term average shoreline change rate was +1.5 ± 0.6 m/yr (Table 3). In both the long-term and short-term time periods there was a pronounced trend of accretion at the north end of the beach and erosion in the south (Fig. 7). In the central and southern sections of Ocean Beach shoreline change and significant wave height change at the 10 m contour are correlated for winter storm conditions from the 1950s to 2000s, with an increase in wave height linked to shoreline erosion (Fig. 8). The statistical correlation for the entire beach is poor, but after excluding part of the northern beach sheltered by the ebb-tidal delta, roughly 50% of the shoreline change can be explained by wave height change.

In the San Mateo region the average long-term shoreline change rate, measured along 10.2 km of sandy coastline, was −0.4 ± 0.1 m/yr, while the short-term average shoreline change rate was −0.6 ± 0.3 m/yr (Table 3). Erosion was observed at virtually all the transects along the San Mateo region during both time periods (Fig. 7).

5. Discussion

5.1. San Francisco ebb-tidal delta evolution

The substantial change in morphology of the San Francisco ebb-tidal delta over the past 130 years provides an example of the responses of an ebb-tidal delta to changes in boundary forcing conditions. Results show the San Francisco ebb-tidal delta experienced periods of both erosion and deposition over time, with a total net loss of 100 ± 52 million m^3 of fine- to coarse-grained sand from 1873 to 2005. Consistent radial contraction of the crest of the delta, despite overall volume gain between 1900 and 1956, demonstrates a change to one or more of the factors influencing its morphologic evolution, including an increase in wave height, reduction in tidal current strength due to a decrease in San Francisco Bay's tidal prism, and/or a decrease in sediment supply.

Ebb-tidal delta size decrease associated with increasing wave energy has been well documented at deltas exposed to different degrees of wave action around the world (Walton and Adams, 1976; Hicks and Hume, 1996). Analysis of the long-term variability of storminess (a proxy for coastal wave activity) in Central California by Bromirski et al. (2003) showed no substantial change since 1858. Similarly, Allan and Komar (2006) show only a negligible increase in average winter coastal wave heights (1.2 ± 1.8 cm/yr) in the study area since 1980. Recent observations of increased coastal wave heights, though not statistically significant trends, could have contributed to ebb-tidal delta contraction over the past few decades, but cannot account for contraction documented over the entire span of this study. The negligible short-term trend and absence of any long-term trend suggest waves are not the main driver of the long-term contraction of the San Francisco ebb-tidal delta.

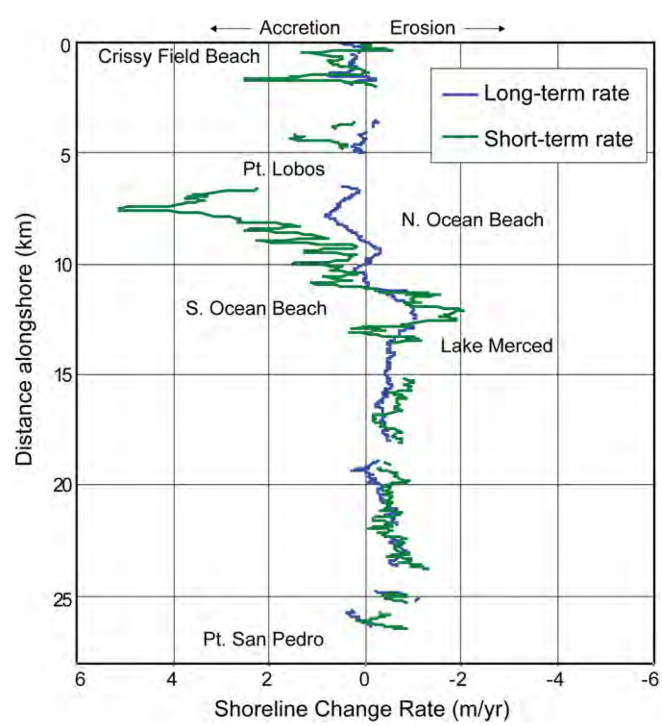

Fig. 7. Shoreline change rates from San Francisco to Pacifica for long-term (1850s/1890s to 2002) and short-term (1960s/1980s to 2002) time periods.

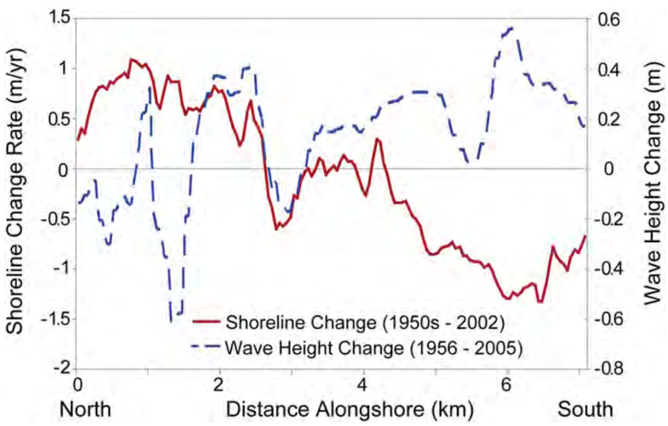

Fig. 8. Shoreline change rate and modeled significant wave height change at the 10 m contour (with parameterized forcing of $H_s = 7$ m, $T_p = 15$ s, $D_p = 270°$) along Ocean Beach from the 1950s to 2000s.

A second hypothesis to explain erosion and contraction of the ebb-tidal delta is a change to the tidal prism of San Francisco Bay, and thus a relative increase in the balance of wave forcing versus tidal currents. A reduction in the tidal prism of San Francisco Bay has been previously documented due to anthropogenic filling of shoals, sedimentation within the bay, and diking of tidal marshes (Gilbert, 1917; Keller, 2009). Gilbert (1917) recorded an average tidal prism of 1.63 billion m^3, Conomos (1979) cited a 1931 value of 1.59 billion m^3, and Keller (2009) cited a current tidal prism value of 1.48 billion m^3. Together, these results indicate a 9% reduction in the estuary's tidal prism. Based on published empirical relationships that relate the volume of a back basin's tidal prism to the volume of sediment in the associated ebb-tidal delta, (Gilbert, 1917; Walton and Adams, 1976; Marino and Mehta, 1987; Hicks and Hume, 1996; Fontolan et al., 2007) even a modest decrease in the tidal prism of San Francisco Bay could lead to profound impacts on the size of the ebb-tidal delta.

A third hypothesis to explain long-term erosion of the ebb-tidal delta is a decrease in sediment supply. Hydraulic gold mining debris and damming of rivers that flow into San Francisco Bay in combination with dredging, borrow pit mining, and aggregate mining within the estuary have altered sediment dynamics. Gilbert (1917) estimated that hydraulic gold mining dislodged roughly 1.3 billion m^3 of material into watersheds that drain into San Francisco Bay from 1849 to 1914, and was the primary reason for 0.9 billion m^3 deposited in the Bay during this time period (Porterfield, 1980). However, Gilbert (1917) estimated that only 38 million m^3 of sediment made it through the Bay to the ocean, including the San Francisco Bar, and that the signal would wane by the middle of the 20th century.

High rates of accretion in Suisun Bay (Cappiella et al., 1999) and San Pablo Bay (Jaffe et al., 1998) from the mid 1800s to 1887 reflect transport of this material from the mines to San Francisco Bay. Dominant accretion in Central Bay (Fregoso et al., 2008) and on the ebb-tidal delta from 1900 to 1950s may also reflect a lag in transport of this material farther down the estuary. Erosion of the delta from 1956 to 2005 may reflect the decrease in hydraulic mining debris supplied to the system and a return to an equilibrium state.

Damming of rivers that flow into San Francisco Bay has also decreased sediment supply to San Francisco Bay. Wright and Schoellhamer (2004) calculated that the three largest dams in San Francisco Bay's watershed have impounded over 80 Mcm of sediment and, along with other anthropogenic impacts, have caused a ~50% reduction in suspended sediment flux from the Sacramento River to San Francisco Bay from 1957 to 2001. While it is unknown if the coarser sediment discharged from the Sacramento River as bedload ultimately settles on the ebb-tidal delta, the dramatic decline in sediment yield indicates the system as a whole is receiving much less sediment as compared to 50 years ago. Since the mid-1950s, Suisun Bay, San Pablo Bay, Central Bay, and the San Francisco ebb-tidal delta have all experienced net erosion (Jaffe et al., 1998; Cappiella et al., 1999; Hanes and Barnard, 2007; Fregoso et al., 2008; Dallas and Barnard, 2009; Barnard and Kvitek, 2010), suggesting a connection between ebb-tidal delta change and change to sediment influx.

In addition to declining sediment input from the Sacramento River, results from this study indicate that a minimum of 200 Mcm of sediment has been removed from the estuary and ebb-tidal delta through dredging, aggregate mining, and borrow pit mining. Of the total, at least 75 Mcm was fine-grained sand to gravel and is comparable with grain sizes on the delta. A majority of the coarse sediment (63%) removed was from Central Bay. Barnard and Kvitek (2010) demonstrated that the rate of sediment loss for Central Bay accelerated three-fold from 1997 to 2008 relative to the rate from 1947 to 1979 (Fregoso et al., 2008), with coarse sediment extraction by aggregate mining playing a dominant role. Analysis by Barnard et al. (in press) of over 3000 bedforms in the area coupled with a validated numerical model strongly suggests net seaward-directed bedload sediment transport. Removal of coarse sediment from Central Bay could therefore potentially reduce sediment supply to the ebb-tidal delta as well as open coast beaches.

5.2. Nearshore wave height change and shoreline change

Changes in morphology of the ebb-tidal delta have altered wave refraction in the region and impacted wave heights along adjacent Ocean Beach. We demonstrate that spatial variation in wave height change along Ocean Beach is a result of morphological changes to shoals offshore of these regions. In the north, deposition offshore has served to protect this section of the beach, dissipating wave energy as waves break farther offshore. In the south, contraction of the delta has resulted in widespread erosion of offshore shoals, and has consequently left this section of the beach more exposed to wave energy. Focusing of waves along southern Ocean Beach due to the shape of the delta (Barnard et al., 2007; Eshleman et al., 2007) and potential increases in nearshore wave height over the past 50 years along the same stretch of beach are likely significant drivers of persistent, ongoing erosion in this region.

Shoreline change rates for the area show that a majority of the open coast shoreline from southern Ocean Beach to Pt. San Pedro has experienced net erosion since the late 1800s. Shoreline change results for the state of California by Hapke et al. (2006) demonstrated that the coastline from Pt. Lobos to Davenport (~80 km south of Pacifica), which includes the Ocean Beach and San Mateo regions covered in this study, has the highest regionally averaged long-term erosion rate in the state. As San Francisco Bay is a major contributor of sediment to the San Mateo coast down to the end of the littoral cell at Pt. Pedro, this pervasive erosional trend indicates that sediment supply from the Bay to the adjacent coastal region has been sharply reduced.

In summary, net long-term erosion of the San Francisco ebb-tidal delta and continued radial contraction of its crest suggests a change to the tidal currents, waves, and/or sediment supply. A slight increase in wave activity and height may have contributed to erosion of the ebb-tidal delta within the past few decades, but the absence of any long-term trend suggests changes in wave energy are not the main driver of long-term delta erosion. Instead, a reduction in the tidal prism of San Francisco Bay has contributed to persistent contraction of the ebb-tidal delta. A decrease in sediment supplied to San Francisco Bay and historic and ongoing removal of coarse sediment from Central Bay may also limit sediment supply to the ebb-tidal delta and open coast beaches. Bathymetric change of the ebb-tidal delta has caused an increase in wave height along southern Ocean Beach and may be a significant factor in the location of an erosional hot spot. Furthermore, accelerating rates of sea-level rise will require an increased supply of sediment to maintain the present-day volume and morphology of the ebb-tidal delta and the wave sheltering benefits it provides.

This research is the most comprehensive study on long-term bathymetric change of the San Francisco ebb-tidal delta to date, and the only study relating anthropogenic activities, ebb-tidal evolution, and shoreline change. A long-term, system-wide perspective, as presented here, is an effective way to study the connectivity of an estuarine–coastal system. The results of this study can be used as an analog for similar systems world-wide, especially in developing countries, many of which have been or will be strongly modified by anthropogenic influences, including damming of drainages, changes in upland land-use (e.g., urban development, agriculture, over-grazing), and elimination of tidal wetlands by development. Future research and management of these systems needs to consider sediment transport pathways from the drainages feeding the estuary out to the open coast, and recognize the cumulative impacts of modifications to the sediment supply. With rising sea-level increasing the accommodation space and therefore the demand for sediment to maintain estuarine–coastal systems in their current form, the efficient management of sediment resources will be essential for preventing additional stresses on these systems, many of which are already experiencing loss of tidal marshes and beaches due to recent limits of the sediment supply.

6. Conclusions

Quantitative analysis of a series of historical and recent bathymetric surveys of the San Francisco ebb-tidal delta provides information on its long-term morphologic evolution and the processes driving the observed change. It is concluded that:

(1) From 1873 to 2005 the San Francisco ebb-tidal delta experienced periods of both erosion and deposition, with total net loss of 100 ± 52 million m^3 of fine- to coarse-grained sand;
(2) A minimum of 200 million m^3 of sediment has been permanently removed from the system by dredging, aggregate mining, and borrow pit mining. At least 50 million m^3 of this total was sand or coarser grained material removed from Central San Francisco Bay and is comparable with grain sizes on the ebb-tidal delta;
(3) Changes to the morphology of the San Francisco ebb-tidal delta have altered alongshore wave energy distribution along adjacent Ocean Beach. Over the past 50 years wave heights have decreased along northern Ocean Beach and increased along southern Ocean Beach, and this increase is coincident with the location of a beach erosion ‘hot spot’ that has persisted for decades;
(4) Shoreline change results indicate a majority of the sheltered, sandy shoreline from Crissy Field Beach to northern Ocean Beach has been stable or experienced net accretion since the late 1800s, with an increase in accretion rates since the 1980s. In contrast, a majority of the exposed, open coast beaches from southern Ocean Beach to Pt. San Pedro have experienced net erosion since the late 1800s, with an increase in erosion rates since the 1960s;
(5) Long-term erosion of the San Francisco ebb-tidal delta and accelerating rates of shoreline erosion along open coast beaches correlate temporally with a reduction in the tidal prism of San Francisco Bay and a decrease in coastal sediment supply, both as a result of anthropogenic activities.

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Exhibit D

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Integration of bed characteristics, geochemical tracers, current measurements, and numerical modeling for assessing the provenance of beach sand in the San Francisco Bay Coastal System☆

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ABSTRACT

Over 150 million m^3 of sand-sized sediment has disappeared from the central region of the San Francisco Bay Coastal System during the last half century. This enormous loss may reflect numerous anthropogenic influences, such as watershed damming, bay-fill development, aggregate mining, and dredging. The reduction in Bay sediment also appears to be linked to a reduction in sediment supply and recent widespread erosion of adjacent beaches, wetlands, and submarine environments. A unique, multi-faceted provenance study was performed to definitively establish the primary sources, sinks, and transport pathways of beach-sized sand in the region, thereby identifying the activities and processes that directly limit supply to the outer coast. This integrative program is based on comprehensive surficial sediment sampling of the San Francisco Bay Coastal System, including the seabed, Bay floor, area beaches, adjacent rock units, and major drainages. Analyses of sample morphometrics and biological composition (e.g., Foraminifera) were then integrated with a suite of tracers including $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopes, rare earth elements, semi-quantitative X-ray diffraction mineralogy, and heavy minerals, and with process-based numerical modeling, in situ current measurements, and bedform asymmetry to robustly determine the provenance of beach-sized sand in the region.

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1. Introduction

A definitive understanding of sediment sources, sinks, and pathways in urbanized coastal–estuarine systems is essential for assessing the current and future effects of sediment-impacting activities, such as dredging operations, aggregate mining, shoreline armoring, and watershed modifications (Duck et al., 2001). More informed management of sediment resources can promote the sustainability of fringing tidal wetlands and beaches, the first line of defense as sea level rises (Vermeer and Rahmstorf, 2009) and potentially larger storms (Graham and Diaz, 2001) increase the vulnerability of coastal environments over the next century and beyond (Jevrejeva et al., 2012), enhancing threats to public safety, vital infrastructure, and ecosystems (Nicholls and Cazenave, 2010).

The physical, biological, geochemical, and mineralogical composition of coastal sediment is a product of multiple factors, including river catchment petrology (Cho et al., 1999), cliff and seafloor geology, biogenic contributions (Lackschewitz et al., 1994), oceanographic and climatic conditions (Bernárdez et al., 2012), residence time, grain size, shape, density, and local hydrodynamics (Steidtmann, 1982). Therefore, understanding the sources of beach sediment can yield important information about transport pathways and anthropogenic impacts, littoral transport directions, and local erosion.

Spatial variations in grain size parameters (i.e., mean grain size, sorting, and skewness) have been used as tool for decades to infer sediment transport pathways, with insight into local sources and sinks (e.g., McLaren and Bowles, 1985; Gao and Collins, 1992; Le Roux, 1994). However, this approach suffers from severe limitations, such as lack of validation data sets for the multiple approaches, uncertainty as to whether the grain size variability is associated with a modification of the hydrodynamic energy or with sediment reworking processes, input uncertainties such as sampling and measurement error, and model uncertainties (Poizot et al., 2008). Preferential sorting on beaches has established heavy mineral analysis as a common tracer for establishing provenance (e.g., Rao, 1957; Morton, 1985; Frihy et al., 1995), where storms, frequent washing of sediments, and wind erosion can focus more dense, darker grains in distinct layers (Da Silva, 1979; Li and

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Komar, 1992). However, from source to sink, the effects of weathering, transportation, deposition and diagenesis must be considered in interpretations (Morton, 1985), and the mechanisms of beach deposition are still poorly understood (Gallaway et al., 2012). Andrews and Eberl (2012) used quantitative X-ray diffraction (qXRD) and SedUnMix, an Excel Macro program, to gain a greater understanding of provenance in a complicated glacial marine system, but were not able to capture exact source rock compositions, a common shortcoming of qXRD. Magnetic properties of sediment have been used as a fast, low cost means to explore sediment provenance in estuaries (Jenkins et al., 2002) and beaches (Rotman et al., 2008), although magnetic signatures are not useful if the magnetic susceptibility of source areas is not distinct, and the results are complicated by the natural particle size variability of the samples (Oldfield and Yu, 1994). Rare earth elements (REE) have been used as a tracer to determine sediment transport pathways (Ronov et al., 1967; Piper, 1974), with numerous studies using REEs to determine coastal sediment provenance (e.g., Munksgaard et al., 2003; Prego et al., 2012), but their universal applicability can be limited by natural abundance. Isotopic analysis (e.g., $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) has often been used in recent years, particularly for mud-dominated seafloor sediments and eolian dust (e.g., Lee et al., 2005; Saitoh et al., 2011), due to their stability and reflection of minerals and rocks with different ages and compositions (Grousset and Biscaye, 2005), but the analysis is expensive and the results can be difficult to interpret (Farmer et al., 2003).

The only means to implement effective local and regional sediment management plans that promote the sustainability of coastal environments is to understand the entire coastal system, from source to sink. However, because any given provenance technique limits the relevance and applicability of the results to discrete portions or processes within a complex coastal–estuarine system, recent studies have utilized multiple techniques. For example, Duck et al. (2001) used bedform asymmetry, grain size distribution, and magnetic susceptibility measurements in an attempt to distinguish the relative contribution of marine and fluvially-derived bedload in a channel of the Tay Estuary, Scotland. Bernárdez et al. (2012) incorporated grain size, total carbon, particulate organic and inorganic carbon, particulate organic nitrogen, X-ray diffraction, heavy mineral separation, and flame atomic absorption spectrometry for metals analysis to determine the provenance of marine sediments off the coast of the northwest Iberian Peninsula. The results of these provenance studies clearly were strengthened by the use of multiple techniques, but the integration of the results in these prior studies was only qualitative.

In this study we present a uniquely extensive, complex, and robust approach to determining sediment provenance in the San Francisco Bay Coastal System, focusing on the pathways for the movement of beach-sized sand from the watershed, through the estuary, and onto open-coast beaches. This study was motivated by major anthropogenic changes to the Bay that began with the influx of hydraulic mining-related sediment from the Gold Rush in the 19th century (Gilbert, 1917), and have continued to the present with extensive indirect and direct impacts on the Bay sediment supply, including widespread watershed modifications (e.g., Wright and Schoellhamer, 2004), and Bay floor aggregate mining and dredging (Dallas and Barnard, 2011), reflected by ~150 million m^3 of erosion from the floor of San Francisco Bay over the last half of the 20th century (Barnard and Kvitek, 2010). This significant erosion of the Bay floor is temporally correlated with similarly high volumes of erosion of the ebb-tidal delta at the mouth of San Francisco Bay (Hanes and Barnard, 2007; Dallas and Barnard, 2009), as well as widespread erosion of adjacent, open-coast beaches (Hapke et al., 2006; Dallas and Barnard, 2011; Barnard et al., 2012a). However, a quantitative physical or geochemical connection has not been established between sediments inside and outside the Bay, nor a definitive causal link driving regional coastal erosion.

Using extensive regional sediment sampling, geochemical and mineralogical analyses, multibeam bathymetry mapping, physical process measurements, and numerical modeling, we developed a semi-quantitative method to integrate and cross-validate the results of nine separate techniques for establishing sand provenance:

1) Grain size morphometrics
2) $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios
3) Rare earth element (REE) composition
4) Heavy minerals
5) Semi-quantitative X-ray diffraction (XRD)
6) Biologic, anthropogenic, and volcanic constituents
7) Bedform asymmetry
8) Acoustic Doppler velocity measurements
9) Modeled residual sediment transport

The multifaceted approach results in a definitive understanding of sand movement in the coastal–estuarine system, thereby providing essential information to promote more efficient management of sediment resources. This unique and complex approach can serve as a model for provenance studies worldwide.

2. Study area

2.1. Physical setting

San Francisco Bay is the largest estuary on the U.S. West Coast (Conomos et al., 1985), and is among the most developed and human-altered estuaries in the world (Knowles and Cayan, 2004). The San Francisco Bay Coastal System comprises four sub-embayments, as well as the open coast littoral cell, extending from Pt. Reyes to Pt. San Pedro, the ebb-tidal delta (i.e., San Francisco Bar) at the mouth of San Francisco Bay, the inlet throat (i.e., Golden Gate), and the Sacramento–San Joaquin Delta mouth (Fig. 1). The region is subjected to highly energetic physical forcing, including spatially and temporally variable wave, tidal current, wind, and fluvial forcing. The open coast at the mouth of San Francisco Bay is exposed to swell from almost the entire Pacific Ocean, with annual maximum offshore significant wave heights (h_s) typically exceeding 8 m, and mean annual $h_s = 2.5$ m (Scripps Institution of Oceanography, 2012). Inside the Bay, wave forcing is less important, except on shallow Bay margins where local wind-driven waves, and occasionally open ocean swell can induce significant turbulence and sediment transport (Talke and Stacey, 2003; Hanes et al., 2011). Tides at the Golden Gate (NOAA/Co-ops station 9414290) are mixed, semi-diurnal, with a maximum tidal range of 1.78 m (MLLW–MHHW, 1983–2001 Tidal Epoch), but due to the large Bay surface area (1200 km^2 at MSL), the Golden Gate strait serves a spring tidal prism of 2×10^9 m^3. This powerful tidal forcing results in peak ebb tidal currents that exceed 2.5 m/s in the Golden Gate, peak flood tidal currents of 2 m/s just inside Central Bay, and even 1 m/s on the edge of the ebb-tidal delta, 10 km from the inlet throat (Rubin and McCulloch, 1979; Barnard et al., 2007). The strongest tidal currents throughout the other sub-embayments are focused in the main tidal channels, commonly approaching 1 m/s (e.g., Wright and Schoellhamer, 2004). Bedforms dominate the substrate (Rubin and McCulloch, 1979; Chin et al., 2004; Barnard et al., 2006, 2011b, 2012b) where sand is prevalent among the highly energetic areas throughout the region, including at the mouth of San Francisco Bay and the deeper portions of Central Bay, San Pablo Bay, and Suisun Bay (Fig. 1), particularly within the main tidal channels. The bottom sediments are mud-dominated in South Bay and in the shallower (<4 m), lower tidal energy areas of Central Bay, San Pablo Bay, and Suisun Bay (Conomos and Peterson, 1977).

Sediments are derived from watersheds of the Sacramento–San Joaquin Delta (i.e., Sierran, notably granitic) and local tributaries, and the local coast range that outcrops along the open coast, in the Golden Gate and Central Bay (i.e., Franciscan Complex, notably chert and serpentine, and younger volcanic and sedimentary rocks) (Gilbert, 1917; Yancey and Lee, 1972; Schlocker, 1974; Porterfield, 1980; McKee et al., 2003; Graymer et al., 2006; Keller, 2009). The modern Bay floor and adjacent open coast seafloor are primarily composed of sand and

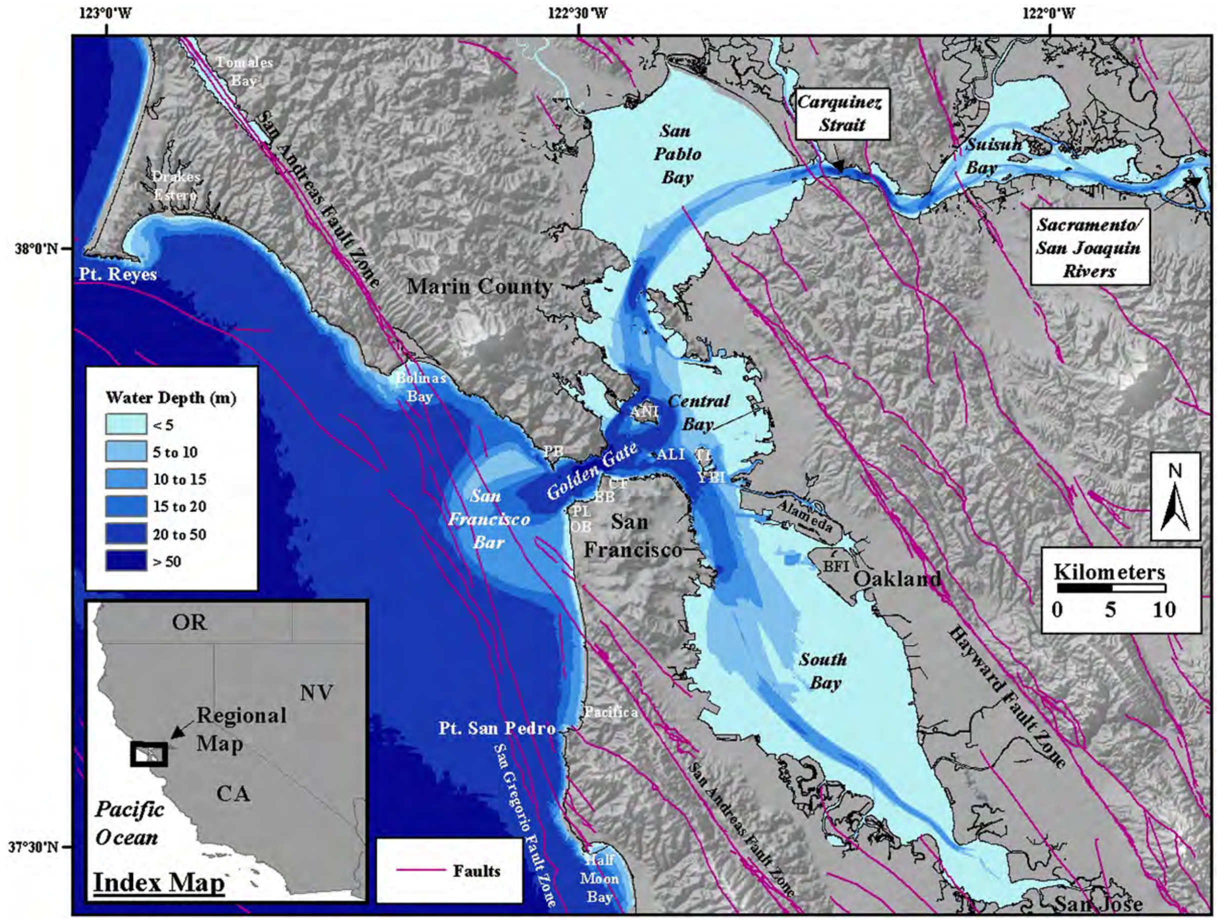

Fig. 1. The San Francisco Bay Coastal System. (ALI = Alcatraz Island, ANI = Angel Island, BB = Baker Beach, BFI = Bay Farm Island, CF = Crissy Field, OB = Ocean Beach, PB = Pt. Bonita, PL = Pt. Lobos, TI = Treasure Island, YBI = Yerba Buena Island).
Fault lines from USGS (2006).

mud of Sierran and Franciscan origin that is actively transported into the region (Keller, 2009), overlying metamorphic and sedimentary bedrock: the shallowest depths to bedrock and intermittent bedrock exposures are most common in Central Bay (Trask, 1956; Goldman, 1969; Carlson and McCulloch, 1970; Chin et al., 2004), within the Golden Gate (Barnard et al., 2006), the northern open coast, and Carquinez Strait (Jachens et al., 2002). The framework geology for the San Francisco Bay Coastal System is described extensively in Elder (2013–this issue).

2.2. Prior work-sediment transport

Historically, the majority of the sediment load to San Francisco Bay was supplied from the Sacramento–San Joaquin Delta (Krone, 1979; Porterfield, 1980), with the Sacramento River producing seven times the sediment yield of the San Joaquin River (Oltmann et al., 1999), a ratio that is still valid (Wright and Schoellhamer, 2005). Prior to the Gold Rush in 1849, Gilbert (1917) estimated sediment supply from the Delta to the Bay was ~1.3 Mt/yr. Ganju et al. (2008) estimated a decrease in mean annual sediment loads to the Delta from a high of greater than 10 Mt/yr in the late 19th century to less than 3 Mt/yr in the latter half of the 20th century, with a dramatic decrease after 1910 attributed to the onset and subsequent cessation of hydraulic mining, followed by major Delta modifications (Knowles and Cayan, 2004). Recent estimates of suspended loads entering the estuary from the Sacramento–San Joaquin Delta range from 1.2 Mt/yr (McKee et al., 2006) to 4 Mt/yr (Shvidchenko et al., 2004), with most of this likely mud-sized, with a comparable amount coming from local tributaries (Lewicki and McKee, 2010). However, newly updated estimates of suspended supply for the period 1995–2010 from the Delta are 0.89 Mt/yr, and 1.43 Mt/yr from local tributaries, indicating that local watersheds are now the dominant source of sediment feeding the Bay (McKee et al., 2013–this issue). Suspended sediment loads decreased by 50% from the Sacramento River from 1957 to 2001, from ~2–3 Mt/yr to 1–2 Mt/yr, or, assuming a linear decrease over that time period, a total reduction of ~25 Mt (Wright and Schoellhamer, 2004; Singer et al., 2008). From water years 1991–1998 to 1999–2007, there was an abrupt, 36% step decrease in suspended sediment concentrations observed inside the Bay, broadly attributed to the depletion of the 'erodible sediment pool' created by hydraulic mining and possibly urbanization, and further reduced by river bank protection, and sediment trapping behind dams and in flood bypasses (Schoellhamer, 2011). However, the transport pathways and ultimate sink of these historically-varying sediment loads has never been established.

The net direction of sediment transport across the Golden Gate, the critical interface that connects the Bay and the open coast, is poorly understood, but paramount to understanding limits on sediment supply within the San Francisco Bay Coastal System. Fram et al. (2007) measured root-mean-squared instantaneous discharges across the inlet throat of 60,000 m^3/s, mean discharges of 600 m^3/s (net seaward), and a mildly stratified channel, while Martin et al. (2007) noted that the direction of the net advective flux of chlorophyll was always seaward. The only direct estimates of suspended sediment transport using in situ measurements across the Golden Gate were conducted by Teeter et al. (1996), who performed repeated inlet cross-sectional transects using boat-mounted acoustic Doppler profiler systems. They observed a clear net seaward transport of suspended sediment of 188,000 Mt over a two week period, with fluxes during ebb flows 44% higher on average than during flood flows. Although direct measurements of bedload transport across the Golden Gate have not been performed, an extensive study of bedform asymmetry covering west-central San Francisco Bay and the mouth of San Francisco Bay suggests a net seaward flux of bedload through the Golden Gate, further confirmed by applying a hydrodynamically-validated numerical model to estimate the net flux of suspended load and bedload across the inlet throat (Barnard et al., 2012b, 2013–this issue-a). A complete summary of sediment transport research in the region can be found in Barnard et al. (2013–this issue-b).

2.3. Prior work-sediment provenance

A number of sediment provenance studies in the San Francisco Bay area have focused exclusively on the mud fraction (e.g., Knebel et al., 1977; Griggs and Hein, 1980; Hornberger et al., 1999; Ingram and Lin, 2002), with fewer studies providing information on sand sources and littoral transport, but typically just the fine and very fine sand fraction (~0.063–0.25 mm; e.g., Moore, 1965; Cherry, 1966; Wong, 2001). Yancey and Lee (1972) identified five distinct heavy mineral assemblages for the Central California coast. This study linked the majority of bottom sediments in North Bay (i.e., Suisun and San Pablo Bays), Central Bay, and the mouth of San Francisco Bay south to Pacifica to a Sierran source delivered to the Bay by the San Joaquin–Sacramento drainage basins (see Fig. 1), suggesting that the dominant regional direction of transport is from the Bay seaward toward the ebb-tidal delta, and then primarily to the south, which the Sierran sedimentary petrographic province of Moore (1965) also strongly suggests. Locally-derived heavy mineral assemblages are more evident for South Bay, and in the immediate vicinity of Pt. Reyes and Bolinas Bay.

Conomos (1963) used heavy and light minerals to determine that most of the sandy sediment in the southern half of South Bay was derived from the Franciscan rocks of local tributaries (primarily Alameda Creek, which enters South Bay along the southeastern shoreline: Fig. 1) entering the sub-embayment, with no sediment from the Sacramento–San Joaquin Delta. The fine fraction of the northern portion of South Bay is well-mixed with the majority of sediment inflow originating from other sub-embayments to the north, but the sand fraction appears locally-derived (Gram, 1966), evidence that the mud and sand fractions are transported by a different set of processes and cannot be used as tracers for each other. Based on surficial grain size distributions and the multibeam, backscatter and sidescan data of Greene and Bizarro (2003), Chin et al. (2010) suggest that the sand in Central Bay is derived from either outside San Francisco Bay, shoreline sediments and outcrops in the vicinity of the Golden Gate (the coarser sands), or from San Pablo Bay (finer sands), with little mixing of the two fractions.

Along the open coast, a major potential source of sediment north of Pt. Reyes is the Russian River mouth, but heavy mineral analysis of beach and inner shelf sediments document a sharp decrease in abundance south of Bodega Head (Cherry, 1964; Minard, 1971; Demirpolat, 1991). The Russian River thus is unlikely to be a significant source of sediment to the San Francisco Bay Coastal System. Cherry (1966) used heavy mineral distribution on several beaches to track littoral sand movement near Pt. Reyes, finding negligible net movement of sand, with most of the beach material locally derived from the less resistant beach-backing cliffs, and inactive transport beyond ~27 m water depth. Wilde et al. (1969) collected over 60 cliff, beach and inner shelf samples in the Bolinas Bay region, finding the major supply of heavy minerals being a granitic source extending directly from the ebb-tidal delta at the mouth of San Francisco Bay, with secondary sources from Bolinas Lagoon and adjacent cliffs. Landward of this lobe, to the north and northeast, Franciscan minerals become increasingly more concentrated. They also established a counter-clockwise transport of sediment within Bolinas Bay with an annual flux of 220,000 m^3, and bottom sediments in a state of quasi-equilibrium.

The actively eroding Franciscan bluffs bordering the Golden Gate are likely a significant local source of coarse sediment, with diagnostic minerals and mineral assemblages found on the ebb-tidal delta (Gilbert, 1917), the ocean floor of the Golden Gate, beaches along the open coast (Moore, 1965), and from west-central San Francisco Bay (Keller, 2009). Two local Quaternary sedimentary formations with Sierran material (Merced and Colma formations) are exposed on Angel Island, from Ocean Beach to Pacifica, and may underlie sediment offshore (Schlocker, 1974; Bruns et al., 2002). Schlocker (1974) interpreted the sand at Ocean Beach as derived locally from these two formations, with mineralogy atypical of the Franciscan Complex. Particularly diagnostic of the Colma Formation is the abundance of magnetite along the heavily eroding section of southern Ocean Beach (Hansen and Barnard, 2010). Based on the physical and mineralogical properties of extensive regional beach and shelf sediment sampling (n = ~200), Moore (1965) concluded that the sand on the ebb-tidal delta and inner shelf to the south in depths less than ~30 m reflected the mineralogy of San Francisco Bay sediments (similar to channel sands west of Carquinez Strait), and was notably distinct from beach and nearshore sediments to the north. He further noted that the littoral zone in this region is largely composed of sediment locally derived from proximal headlands, cliffs, watersheds, and bays, and that littoral zone mineralogy changes alongshore when local source rock changes or physical boundaries occur. However, the composition of beach sands south of the Golden Gate are less variable than the local cliffs, suggesting only minor inputs from that local source, but with distinct southerly littoral transport. Schatz (1963) integrated the grain size and heavy mineral work of Trask (1953) and Kamel (1962) to suggest a possible pathway of sand from north to south across the crest of the ebb-tidal delta, and then toward shore at the southern end of Ocean Beach, a pathway that was later hypothesized by Battalio and Trivedi (1996).

Wong (2001) isolated the fine sand fraction (0.063 to 0.250 mm) of heavy minerals from samples collected on the continental shelf from approximately Pt. Reyes to Half Moon Bay, identifying two primary heavy mineral assemblage groups that dominated the region: 1) sand derived from granitic rocks, particularly Sierran, extending from approximately Bolinas Bay to Half Moon Bay, broadly similar to the region designated as the Sierran heavy mineral province by Yancey and Lee (1972), and 2) sand derived from Franciscan rocks, found predominantly from Bolinas Bay to Pt. Reyes. However, most of the sediment samples are well outside the active littoral zone, and believed to be relict deposits from at least the mid-Holocene. These prior studies can offer only broad guidance to our present work, as none of this research isolated the beach-sized sand fraction and traced it from source to sink, including the Bay, open-coast beaches, and the littoral zone.

3. Methods

Below is a brief summary of the methods used in this study. For a more comprehensive description of the methods for each individual technique please refer to the references listed, particularly within this special issue.

3.1. Pilot study of bulk geochemistry

Prior to the full beach-sized sand provenance study, eight surficial sediment samples were collected from beaches in the vicinity of the Golden Gate and nearshore to determine if bulk sediment chemistry could distinguish sources along the open coast (Fig. 2). Bulk sediment samples were ground to <0.15 mm and decomposed with a four-acid total digestion (Briggs and Meier, 2002). Thirty-seven major, minor, trace and rare earth elements were analyzed on a Perkin Elmer Elan

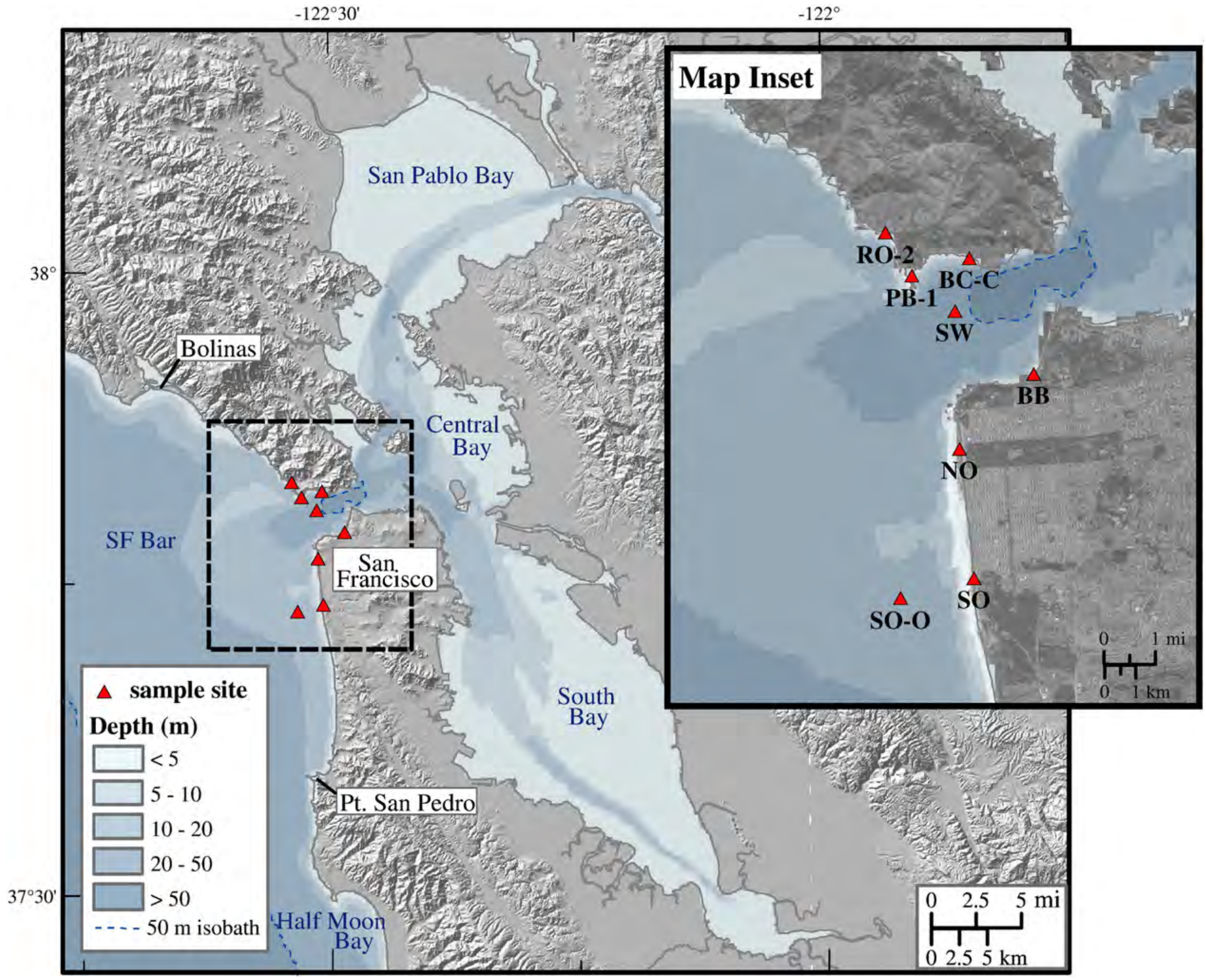

Fig. 2. Location of the pilot samples analyzed for bulk geochemistry. (RO = Rodeo Beach, PB = Point Bonita, BC = Bonita Cove, BB = Baker Beach, NO = north Ocean Beach, SO = south Ocean Beach, SW = sand wave field, SO-O = south Ocean Beach offshore).

6000 inductively-coupled plasma mass spectrometer. Limits of determination, defined as five times the standard deviation of the blank, are ≤0.01 wt.% for major elements and <1 ppm for most minor and most trace elements.

3.2. Sediment sampling and geochemistry

A total of 425 sediment and/or rock samples were collected from major Bay tributaries, the Bay and seafloor, Bay and outer coast beaches, and bedrock outcrops within the San Francisco Bay Coastal System and associated watersheds (Fig. 3). The majority of samples used in this study (n = 255) were collected over the course of 3 cruises (Table 1), with seafloor grab samples collected in early 2010 and beach and tributary samples between 2010 and 2012. An additional 170 seafloor grab samples were collected in late 2011/early 2012 and were incorporated solely for the grain size morphometrics portion of this study (see Section 3.2.1). Grain size of surface samples from a series of earlier studies (mostly collected from 2005 to 2008) throughout the region (n = 290) were also incorporated into the grain size analyses.

To characterize the geochemical signature of potential source materials, bed sediment was collected from the Sacramento River (3 sites), San Joaquin River (2 sites), and from nine smaller local tributaries that drain directly into the Bay (Napa and Guadalupe rivers; Alameda, Calaveras, Corte Madera, Del Presidio, San Francisquito, Sonoma, and Wildcat creeks) as well as the Russian River, which drains to the Pacific Ocean north of Bodega Bay (Fig. 3). Tributary samples were extracted from the top ~10 cm of sediment deposits. All of the tributary samples were collected along the river's edge by hand trowel, with the exception of two Sacramento and one of the San Joaquin River samples which were collected in the center of the channel. Source rock samples were extracted using a rock hammer at subaerial outcrops along the open coast from the major geologic rock sources (i.e., granite, basalt, chert, sandstone, and serpentinite). Forty-two surface sediment samples were collected from beaches throughout the study area. To assess transport from these sources and potential mixing and redistribution throughout the study area, surface sediment (top ~10 cm) was collected using a clam shell grab sampler from a total of 169 bay/ocean floor samples throughout the Bay and along the open coast. The surficial sediment sampling strategy was intended to capture the most active sediment layer, and therefore reflect the modern provenance of sediment. However, in some cases, the upper 10 cm of the substrate may penetrate into eroding sediments that are more representative of historical rather than contemporary conditions, and therefore the integration of co-located proxy provenance techniques (i.e., bedform asymmetry, numerical modeling, and/or velocity measurements) will be particularly effective in reducing impact of this potential bias. Prior to standard grain size processing, a small fraction of select sediment samples was selected for biologic, anthropogenic, and volcanic constituent analyses (McGann et al., 2013–this issue). The remaining fraction of all sediment samples were then cleaned with hydrogen peroxide to remove organics, disaggregated in an ultrasonic bath, washed with deionized water to

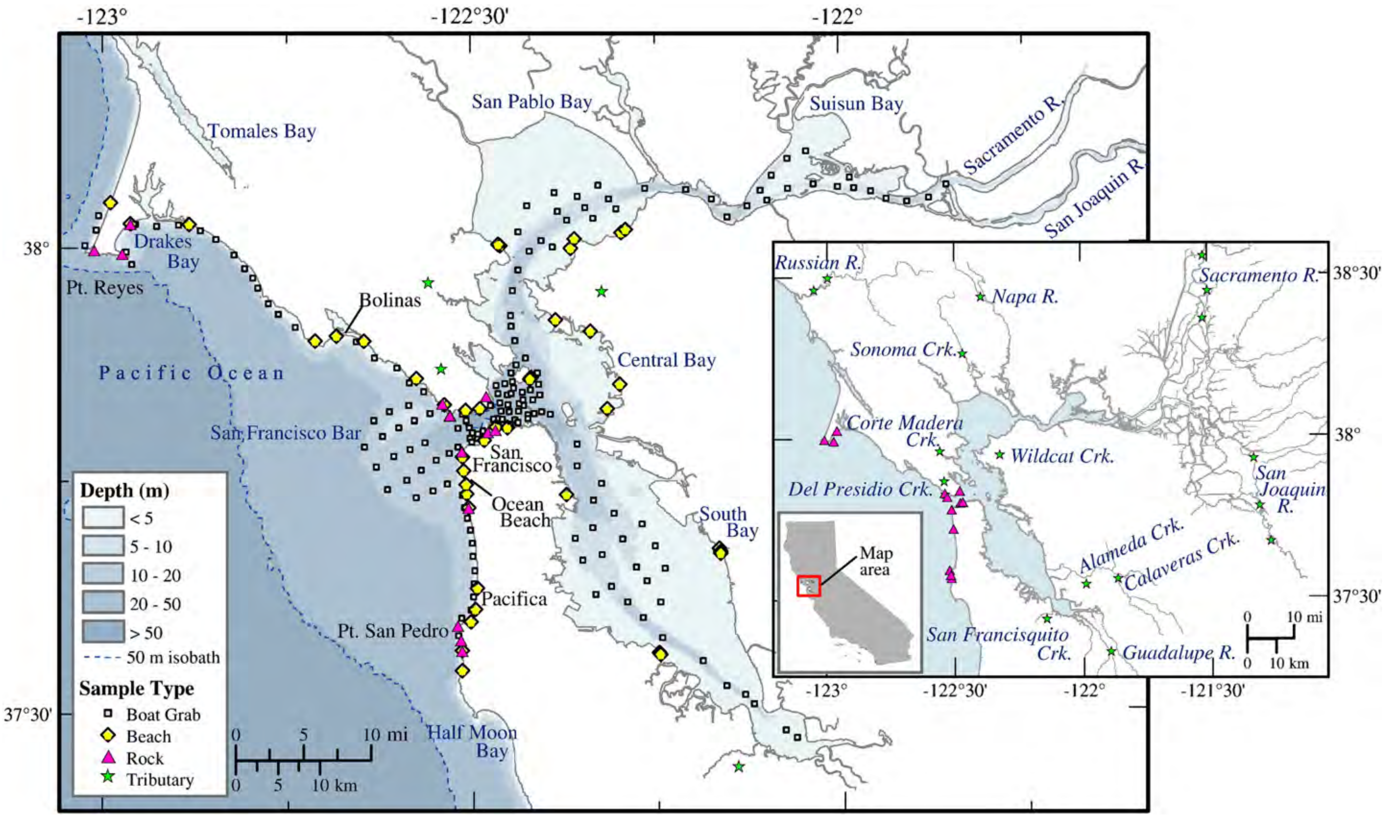

Fig. 3. Location and source of sediment samples included in this study.

remove salt, and the gravel fractions isolated from sand and mud fractions via wet sieving. Particle size analysis on the mud and sand fractions was performed using a laser diffraction particle size analyzer, and gravel size was determined by wet sieving.

Based on the mean D_{10} to D_{90} range of the open coast beach samples (n = 19) of 0.15–0.5 mm, the beach-sized sand fraction of 101 sediment samples was split for geochemical analyses (Fig. 4). From the first split, two size fractions were isolated, 0.063–0.25 mm and 0.25–0.5 mm, and the target weight measured out for heavy mineral analysis:

- Fraction 1a — ~50 g (min. 10 g) for fine sand heavy mineral analysis
- Fraction 1b — ~50 g (min. 10 g) for medium sand heavy mineral analysis.

Using the second split of the sand fraction, the particle size range from 0.15 to 0.5 mm was isolated, shell was removed by acid leaching and the sample was rinsed thoroughly with ultra-pure deionized water. After being pulverized to a fine powder, bedrock samples (n = 18) were also leached and cleaned. The cleaned, salt-free, shell-free samples were split to get target weights for additional analyses:

- Fraction 2 — ~5 g for $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ analyses (min. 1 g)
- Fraction 3 — ~10 g for semi-quantitative XRD analysis (min. 5 g)
- Fraction 4 — ~10 g for rare earth element analysis.

Table 2 lists the total number of samples analyzed in this study, with their locations plotted in Fig. 5. A complete list of the sample locations and analyses performed is archived at Pangaea (http://dx.doi.org/10.1594/PANGAEA.803904).

Table 1
Cruise dates and number of samples collected (USGS, 2010, 2011).

Cruise ID	Dates	Description	Count
S-7-10-SF	1/2010	USGS cruise, SF Bay grab samples	59
S-8-10-SF	3/2010	USGS cruise, SF Bay and coastal grab samples	110
B-2-10-SF	3/2010–3/2012	Sediment collected from beaches and tributaries, rock from outcrops	86
B-5-11-SF[a]	8/2011	RMP sediment cruise coordinated by SFEI and run by Applied Marine Sciences, Inc., SF Bay grab samples	51
S-1-12-SF[a]	1/2012	USGS cruise, SF Bay and coastal grab samples	119

[a] Samples from these cruises were used solely for grain size analyses.

3.2.1. Grain size morphometrics

A simplified sediment trend analysis was performed by evaluating spatial variations in grain size parameters (mean grain size, sorting, and skewness) throughout the study area using a Geographic Information System (GIS). Surface grab samples were processed using standard procedures. Particle size distributions of the mud and sand fractions were analyzed separately using a Beckman Coulter LS100Q and the gravel fraction by wet sieves. Statistics were calculated using the method of moments for the 169 surface grab samples collected in early 2010 (Table 1) and for an additional 170 samples collected in August 2011 and January 2012. Mean grain size was also compiled from a series of earlier studies (samples mostly collected from 2005 to 2008) focusing primarily on western Central Bay, the Golden Gate and the San Francisco Bar (n = 290). The data sets were combined and interpolated to create continuous surface representations of each of three statistics of interest (mean grain size, sorting, and skewness) using a triangular interpolated network (TIN) algorithm. The TINs were then converted to raster surfaces with a horizontal resolution of 300 m. The Flow Direction tool in the ArcGIS Spatial Analyst Toolbox was used to create surfaces of

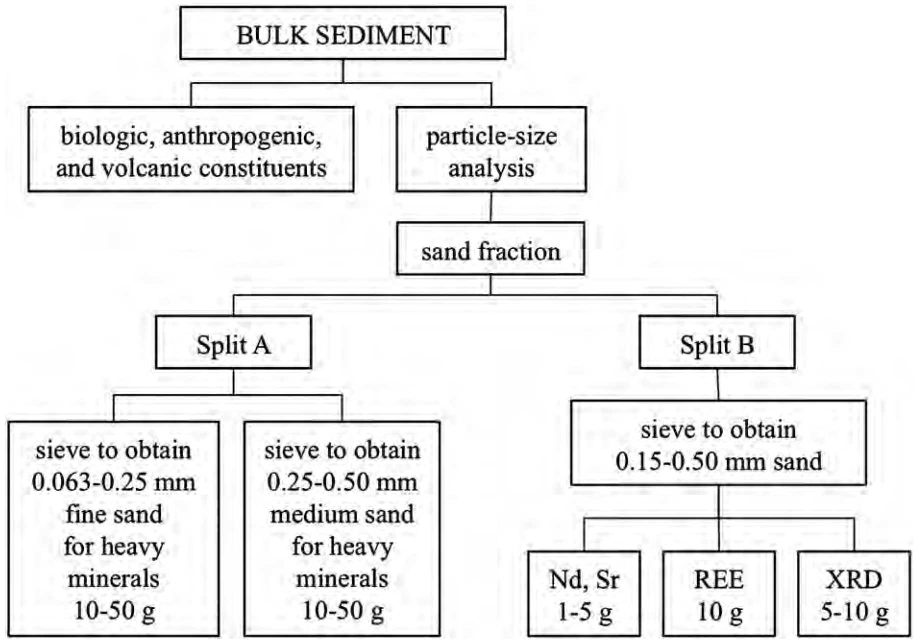

Fig. 4. Flow chart of geochemical analyses.

inferred sediment transport direction for each of the three statistics. The Flow Direction tool evaluates each individual grid cell within a raster and assigns a direction to that central cell based upon the greatest decrease in value between it and the eight surrounding grid cells. In this instance, flow direction for the three separate surfaces are derived from the greatest decrease in: (1) mean grain size (sediment fining), (2) standard deviation (better sorting), and (3) skewness (more negatively skewed in phi units, indicating a tail of coarser sediments). To assimilate results from the three different statistics, the study area was divided into 3 × 3 km blocks and the dominant transport direction within each block assigned. In blocks where the inferred sediment transport directions from at least two of the three parameters were within the same 90 degree quadrant of one another, the directions were averaged to calculate transport direction.

3.2.2. $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ isotopic ratios and trace elements

Solid phase $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios were determined following procedures presented in Weis et al. (2006). Solid phase isotopic ratios were measured using Thermal Ionization Mass Spectrometry (TIMS) and the isotopic ratios were normalized to correct for mass fractionation using reference $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ activity ratios. The normalized $^{143}Nd/^{144}Nd$ ratios were converted to ε_{Nd} using a value of 0.512636 for CHUR (chondritic uniform reservoir) (Rosenbauer et al., 2013–this issue).

Table 2
Number of samples used for each type of analysis by sample origin.

Analysis	Sample origin				Total
	Seafloor	Beach	Rock	Tributary	
Grain size	339	42	0	24	405
X-ray diffraction	61	27	18	13	119
Rare earth elements	58	27	16	16	117
$^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$	46	16	10	15	87
Heavy minerals	44	8	1	10	63
Biologic/anthropogenic[a]	298	0	0	0	298

[a] Analyses included additional samples collected during earlier USGS and SFEI cruises. See McGann et al. (2013–this issue).

3.2.3. Rare earth elements

A complete trace element characterization, including the suite of rare earth elements (REE) was carried out (Rosenbauer et al., 2013–this issue). Each sediment sample was fused by lithium metaborate, dissolved using dilute HNO_3, and analyzed by high-resolution inductively-coupled plasma mass spectrometry (HR-ICP-MS) on a Thermo Scientific Element 2. Precision with known calibration materials was within 2σ error of literature and recommended values. Procedural duplicates and replicate measurements showed excellent agreement, with relative standard deviations (RSD) less than 5%. REE values were chondrite normalized using values reported in Anders and Grevesse (1989), except for yttrium (Y) whose chondrite normalizing value was obtained from Bau et al. (1996). Cerium (Ce) and europium (Eu) anomalies were calculated using the formulas provided by Bau et al. (1996).

3.2.4. Heavy minerals

Sediment samples were selected from the 0.063 and 0.25-mm size fraction (or, if not enough sample was available, from the 0.25 to 0.50 mm size fraction) for heavy mineral analysis. Samples were separated in tetrabromoethane diluted to a specific gravity of 2.90; both the light and heavy (floating and sinking, respectively) grains were retrieved. The heavy grains were microsplit to about 1000 grains and mounted on glass slides. Grains were identified and counted by optical properties determined on a petrographic microscope for 63 samples. The counts were normalized as percent of total non-opaque grains and a cluster analysis was applied (Wong et al., 2013–this issue).

3.2.5. Semi-quantitative X-ray diffraction bulk sand mineralogy

The samples (n = 119) were powdered, X-rayed, and mineral peak height counts multiplied by published weighting factors and summed to 100%. Samples were analyzed using a Philips XRD with graphite monochromator and XRD digital scans were analyzed using Philips X'Pert High Score search and match function to identify peaks and qualitative mineral composition. Cluster analysis was performed on raw scan data using Philips X'pert High Score with default settings. Cluster analysis is an automatic four-step procedure that compares each scan with all other scans and then generates a distance matrix that determines the number of "meaningful" clusters of the most representative member and of the furthermost members of each cluster. Principal

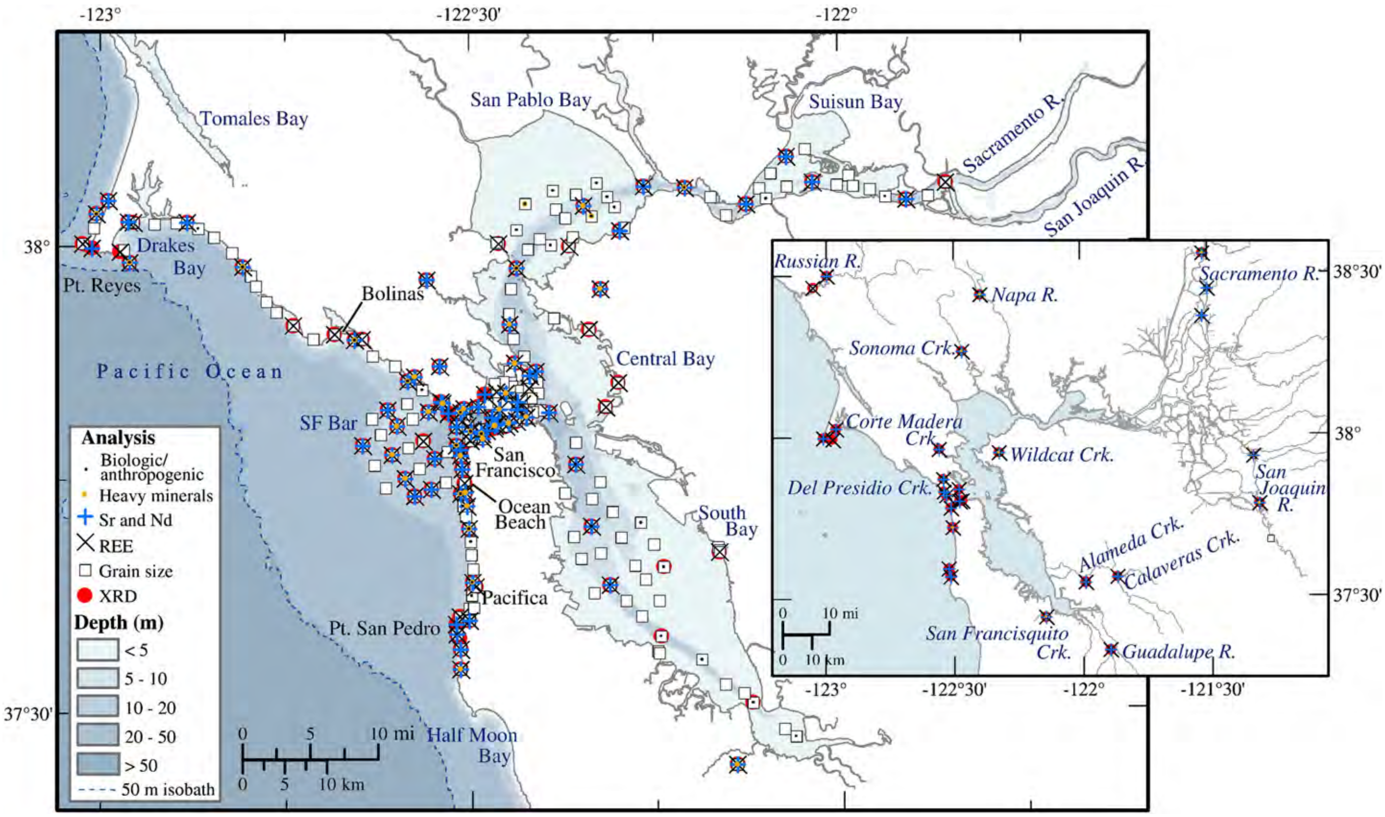

Fig. 5. Location of sediment samples and type of geochemical analyses performed.

Components Analysis (PCA), which is an independent method of visualizing and judging the quality of the clustering, was also used. The scans were compared using the matching algorithm provided for qualitative phase identification (Hein et al., 2013–this issue).

3.2.6. Biologic, anthropogenic, and volcanic constituents

Bulk sediment samples for constituent analysis were collected from 298 sites by the San Francisco Estuary Institute (SFEI) from 1995 to 1998 and by the U.S. Geological Survey (USGS) in 1998 and 2010 (Fig. 6). Benthic foraminifera and representative specimens of other organic and inorganic constituents were picked from the sieved sediment and identified. Of the 298 samples, 280 were picked of all or a split (>300) of the foraminifera present; the remaining 18 samples were scanned for the presence of foraminiferal species. Relative foraminiferal species abundances from the 1995–1998 SFEI and 1998 USGS studies were converted to presence/absence data to be analogous to the 2010 USGS data. Once converted, a Q-mode cluster analysis was utilized to describe the relationship between the benthic foraminiferal assemblages. The cluster analysis grouped the samples according to their degree of similarity. Clustering was based on a square root transformation of the data, a Sørenson similarity coefficient, and amalgamated by a group-averaged linkage strategy. In addition, volcanic glass from five sites was described petrographically and analyzed by electron microprobe. The results were compared to the USGS tephra geochemical database to identify their source (McGann et al., 2013–this issue).

3.3. Bedform asymmetry

The asymmetry of ~45,000 bedforms was measured from 13 multibeam bathymetry surveys performed between 1999 and 2010 in the San Francisco Bay Coastal System (Fig. 7) to infer the bedload transport directions. Point measurements were spatially-averaged into 25,450 2500-m^2 grid cells (50 m × 50 m) using a standard inverse distance weighting technique. The inferred transport direction (ebb or flood) was based on the assumption that bedforms migrate in the direction of the steep lee face (e.g., Van Veen, 1935; Stride, 1963; Allen, 1968; McCave and Langhorne, 1982; Knaapen, 2005), an assumption that has been broadly validated in the San Francisco Bay region by near-bottom current measurements (Rubin and McCulloch, 1979) and numerical modeling (Barnard et al., 2013–this issue-a).

3.4. Measured residual currents

The long-term (months to years) net sediment transport direction is often assumed to coincide with the residual current direction. Several long-term measurements of current velocities have been made within San Francisco Bay and the immediate open coast. We synthesize some previously reported residual current analyses in South and Suisun Bays and present results of measurements obtained at the seaward end of the shoals outside the Golden Gate, along Ocean Beach to the south of the Golden Gate, and in the vicinity of Crissy Field, immediately east of the Golden Gate along the north shore of San Francisco (Fig. 7).

Cheng and Gartner (1984) and Walters et al. (1985) presented residual current directions from a suite of current meters deployed in Suisun and South Bays. Mechanical current meters were mounted on rigid moorings or tethered partially through the water column at numerous stations throughout the Bay during the years 1979 through 1982. Current meter sampling rates were set to one sample every 10 min for the 1979 and 1980 deployments and increased to every 2 min for the later measurements. In waters 10 m or deeper, two mechanical current meters were deployed simultaneously at each station, one within ~3 m of the bed and one at 7 m above the bed. Data collection at each station used in the residual analysis ranged between two and three months.

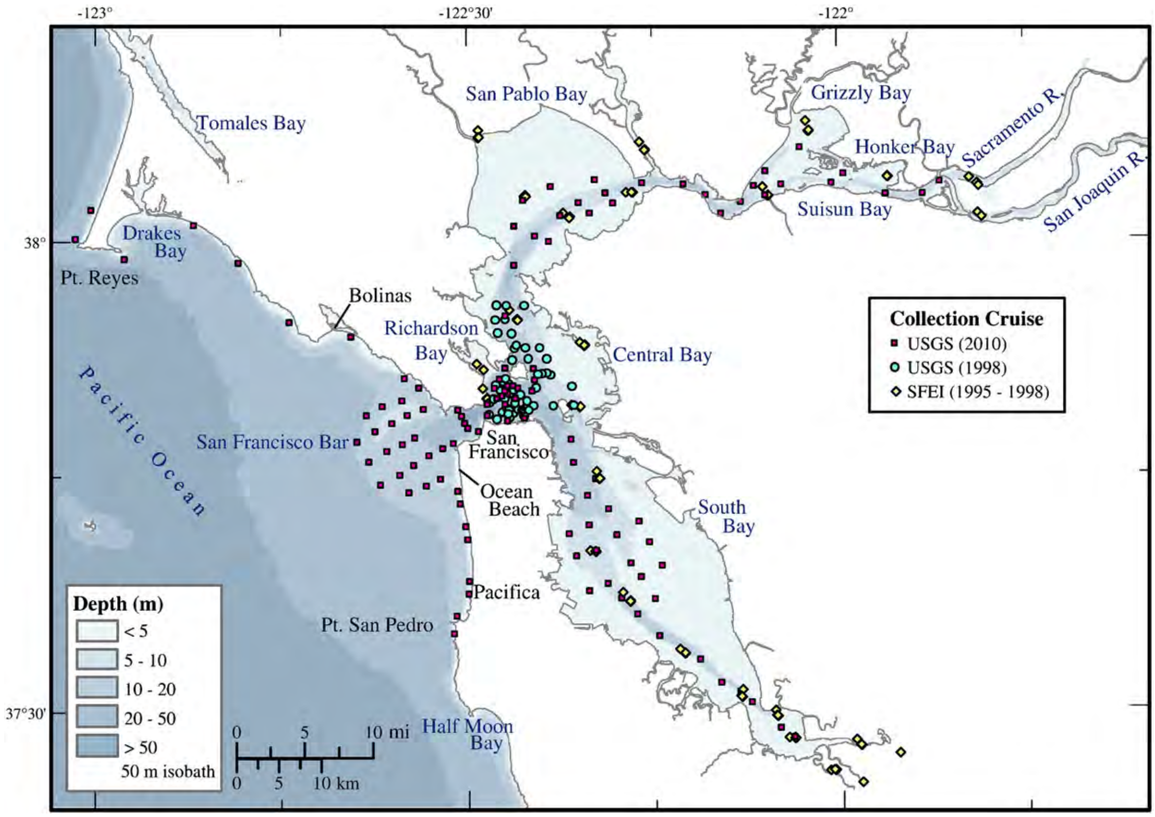

Fig. 6. Location of samples analyzed for biologic, anthropogenic, and volcanic constituents.
Sites include those collected by San Francisco Estuary Institute (SFEI) from 1995 to 1998, as well as those collected by the USGS in 1998 and 2010 (USGS, 1998, 2010).

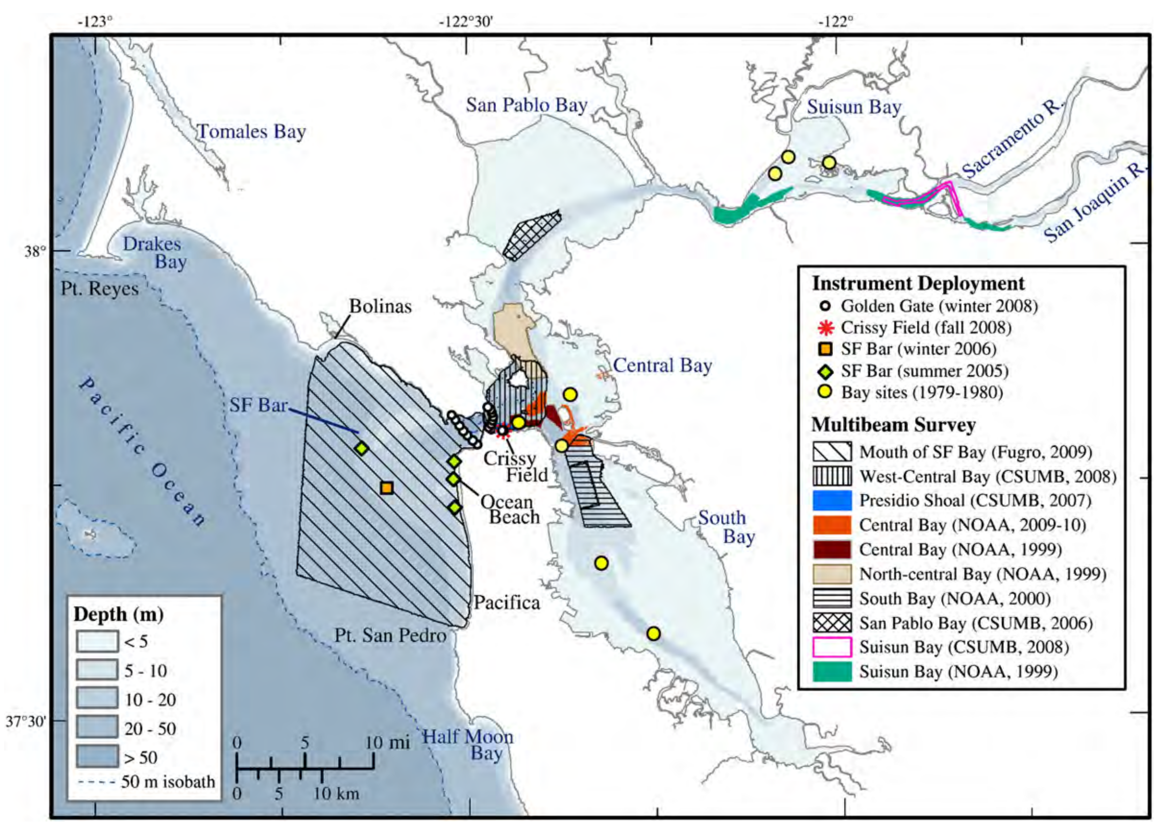

Fig. 7. Multibeam bathymetry data coverage and in situ current measurement locations.

Measurements along the outer coast and Crissy Field were obtained in 2005–2008 (Barnard et al., 2007; Hansen and Barnard, 2010; Hanes et al., 2011) with acoustic Doppler profilers (ADPs; Table 3, Fig. 7). Residual currents were calculated for the bottom bins (within 3 m of the seabed) and depth-averaged over all available bins (bin heights ranged from 0.25 m to 1 m, depending on total water depth) as measured with the current profilers. Exploiting the modern technology of ADPs, sediment flux estimates were also calculated with the acoustic backscatter intensity following the method described by Gartner (2004). Backscatter intensity data were corrected for beam spreading and water absorption, and suspended sediment concentrations computed with calibration parameters obtained from a measurement campaign at the Golden Gate (Erikson et al., 2013–this issue). The difference between residual current directions calculated with vector averaged currents and those multiplied by estimated suspended sediment concentrations was small (<15°).

Residual current results presented herein were computed using a low pass filter (cut-off frequency $= 8.4175 \times 10^{-6}$ Hz) for the 2005–2008 data. Calculations were done on time-series data reduced to an available maximum even multiple of the M_2 tidal period as this is by far the most dominant constituent in the Bay.

3.5. Numerical modeling

To investigate physical processes and sediment transport in the San Francisco Bay Coastal System, a coupled Delft3D hydrodynamic model FLOW and SWAN (Simulating WAves Nearshore) wave numerical model was created (Elias and Hansen, 2013–this issue). Delft3D FLOW forms the core of the model system simulating water motion due to tidal and meteorological forcing by solving the unsteady shallow water equations (Stelling, 1984; Lesser et al., 2004). The FLOW model consists of six two-way coupled domains of varying resolution for optimal computational efficiency. Given the large spatial scale involved with solving the inlet dynamics, and to achieve acceptable model run times, all flow grids were run in depth-averaged mode (2DH). The spectral wave model SWAN (version 40.72ABCDE; Holthuijsen et al., 1993; Booij et al., 1999; Ris et al., 1999) was applied in stationary, third-generation mode to propagate waves from well offshore of the continental shelf to the coastline and into the Bay. The hydrodynamic and wave models were run in quasi-nonstationary mode, a two-way coupling (15-minute intervals) of a nonstationary hydrodynamic calculation in combination with regular stationary wave simulations. The Online Morphology addition to Delft3D is used to compute sediment transport in the flow domains (Lesser et al., 2004). The TRANSPOR2004 transport equations are used to model the movement of non-cohesive sand fractions due to suspended and bed-load sediment transports. The bed was schematized as a single sediment fraction (representative for the ebb-tidal delta deposits) with a D_{50} of 0.25 mm.

Long term (multi-year) simulations would be needed to create representative sediment transport patterns, but such simulations are computationally unfeasible given the high resolution and spatial extent of the model. Instead, input schematization techniques (De Vriend et al., 1993; Lesser, 2009) were used to schematize the wave and tidal boundary forcing to create a representative set of wave conditions and a single 24.8 hour tidal cycle derived from the calibrated constituents. The total wave-averaged transports are obtained by running the coupled wave-flow model for each of the 24 wave cases over one 24.8 hour representative tidal cycle. The tide-cycle-averaged velocity and sediment transport for each simulation were then weighted by the normalized probability of occurrence of each wave case. The probability weighted results were then summed to generate an ensemble of all 24 wave cases to calculate the residual sediment transport. For additional information on modeling details, including calibration and validation, see Elias and Hansen (2013–this issue).

3.6. Integration of techniques

In order to assimilate the results of all provenance approaches and develop a best estimate of beach-sized sand transport pathways, a semi-quantitative user-interface tool was developed using GIS software. The study area was divided into 3 × 3 km blocks (n = 216), and for each block the user could choose from 8 compass directions for inferred transport direction, and 3 levels of confidence (high (3), medium (2), low (1)), based on the data available for each technique (Fig. 8, Table 4). In <10% of the grid cells there was not enough sampling data available locally or regionally to make an entry for any technique. After the results for each of the individual techniques were input into separate data files, the results were compiled and outliers removed by eliminating individual transport vectors falling outside of a 180 degree radius of the majority of data. The mean transport direction (weighted by confidence) and average confidence values for each block was calculated. A final weighted confidence was assigned based on the number of entries, i.e., greater weight was given to blocks with entries from a greater number of techniques driving the result, such that:

$$\text{weighted confidence} = (\text{number of entries}) \times (\text{mean confidence score}).$$

The weighted confidence for each block was reflected in the size of the arrow in the final map of beach-sized sand (i.e., 0.15–0.50 mm for isotopes, REEs, and XRD, 0.063 mm–0.5 mm for heavy minerals) transport pathways.

4. Results and interpretation

The complete geochemical, grain size, and biologic, anthropogenic, and volcanic constituents data described in the following sections (i.e., 4.1–4.4) are permanently archived at Pangaea (http://dx.doi.org/10.1594/PANGAEA.803904).

Table 3
Sampling sites and instrumentation used for 2005–2008 current measurements at the outer coast and Crissy Field. See Fig. 7 for mapped locations.

Site ID	Deployment dates	Depth (m)	Lat (DD)	Long (DD)	ADP mfg. & frequency
Ocean Beach					
Site 2	06/21/05–08/16/05	11.5	37.7560	122.5200	RDI 1.2 MHz ADCP
Site 3	06/21/05–08/16/05	14.6	37.7260	122.5180	RDI 1.2 MHz ADCP
Site 4	06/21/05–07/26/05	21.1	37.7890	122.6430	Nortek AWAC 1 MHz
Site 3	01/12/06–02/06/06	13.4	37.7260	122.5180	Nortek AWAC 1 MHz
Site 5	01/12/06–02/11/06	13.9	37.7470	122.6090	RDI 1.2 MHz ADCP
TV1	01/16/08–05/19/08	12.4	37.7404	122.5210	Nortek AWAC 1 MHz
Central Bay–Crissy Field					
CF2s	09/08/08–09/26/08	4.9	37.8070	122.4507	Nortek AWAC 1 MHz
CF1j	01/14/08–01/30/08	4.9	37.8085	122.4679	Nortek AWAC 1 MHz
CF2j	01/14/08–01/30/08	4.4	37.8070	122.4507	Nortek AWAC 1 MHz

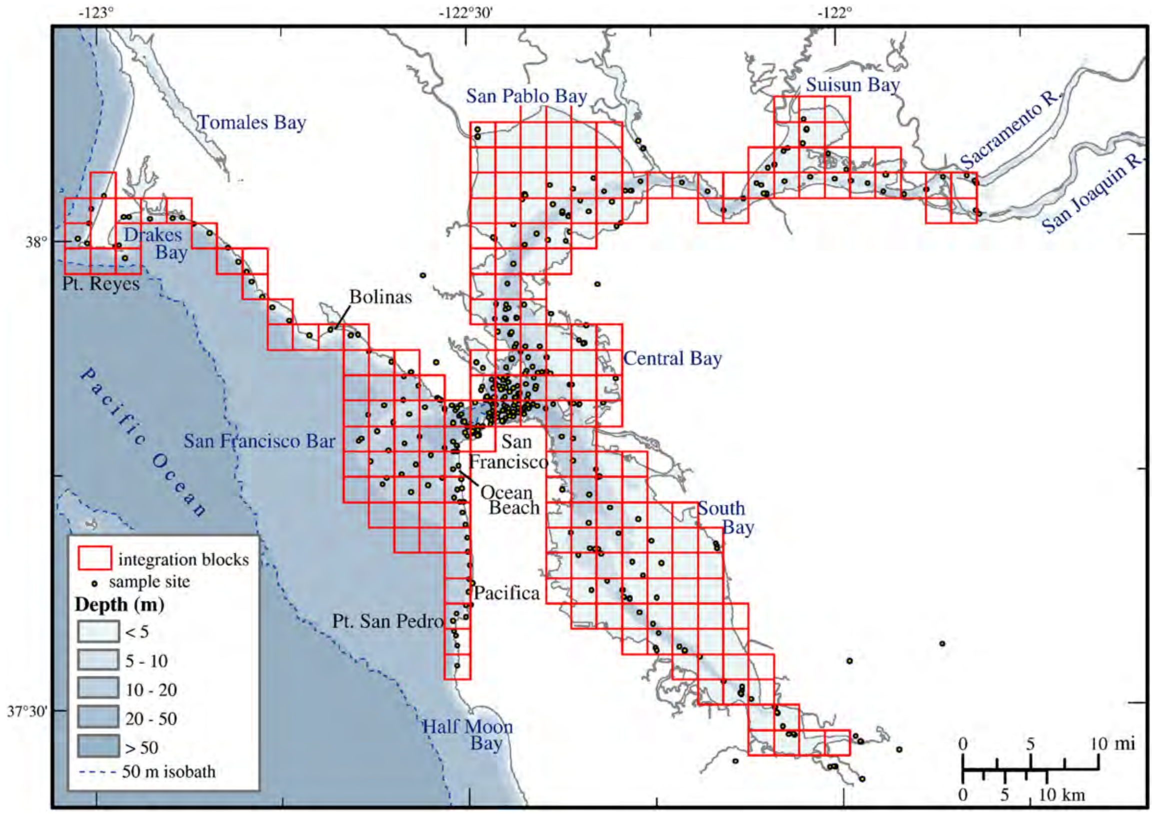

Fig. 8. Sand provenance integration grid based on 3-×3-km square blocks.

4.1. Pilot study of bulk geochemistry

There were distinct bulk geochemical differences among sediments from the outer coast pilot study. In the vicinity of San Francisco, sediment at Baker Beach, northern Ocean Beach, and the sand wave field in the Golden Gate had iron to aluminum ratios (Fe/Al) more similar to granitic and felsic volcanic rocks than Franciscan rocks (Fig. 9), suggesting a Sierran source. North of the Golden Gate (Rodeo Beach, Bonita Cove, Point Bonita) and south of San Francisco (southern Ocean Beach, offshore of southern Ocean Beach) sedimentary Fe/Al ratios fall along a mixing line with Franciscan chert and average sandstone at one end, and Franciscan shale, average basalt and average shale at the other. Sediment at Point Bonita, southern Ocean Beach, and offshore of southern Ocean Beach were enriched in chromium (Cr) relative to Franciscan rocks (data not shown). The enrichments at and offshore of southern Ocean Beach are consistent with the input of Cr-enriched heavy minerals such as Cr-magnetite or chromite from the Colma Formation which outcrops along the coast. At Point Bonita the Cr enrichment was accompanied by high vanadium (V) content, and could be related to the metamorphic history of this site. In summary, based on bulk sediment geochemistry it appears that local sediment sources predominate along the coast north of the Golden Gate and south of San Francisco, while a Sierran source supplies sediment to northern San Francisco beaches (i.e., Baker Beach, north Ocean Beach) and the seafloor of the Golden Gate.

4.2. Grain size morphometrics

The only spatially coherent transport patterns that emerged from the analysis of grain size parameters (Fig. 10) were west of the Golden Gate, where the inferred transport direction in 82% of the 3×3 km blocks fell within ±90° of the average transport direction calculated using all of the techniques applied in this study. Agreement east of the Golden Gate was not as good, with only 62%, 52%, and 48%

Table 4
Confidence intervals for the sand provenance techniques. (SQA = semi-quantitative assessment).

Technique	Diagnostic	High (3)	Medium (2)	Low (1)	No entry
Grain size morphometrics	Grain size, standard deviation and skewness	N/A	N/A	Agreement of two or more metrics in same quadrant	Agreement of less than two metrics in the same quadrant
$^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$	Cluster analysis	SQA	SQA	SQA	SQA
REE composition	Cluster analysis	SQA	SQA	SQA	SQA
Heavy minerals	Cluster analysis	SQA	SQA	SQA	SQA
XRD	Cluster analysis	SQA	SQA	SQA	SQA
Misc. constituents	Cluster analysis	SQA	SQA	SQA	SQA
Bedform asymmetry	Asymmetry (%)	$A \geq 20\%$	$20\% > A \geq 10\%$	$10\% > A \geq 5\%$	$A < 5\%$
Residual current measurements[a]	Duration of deployment	$D \geq 3$ months	3 months > $D \geq 1$ month	1 months > $D \geq 2$ weeks	$D < 2$ weeks
Model — outer coast and Central Bay	Rate (m^3/d/m)	$S \geq 10^{-6}$	$10^{-6} > S \geq 10^{-8}$	$10^{-8} > S \geq 10^{-10}$	$S < 10^{-10}$
Model — South Bay and North Bay	Rate (m^3/d/m)	N/A	$S \geq 10^{-7}$	$10^{-7} > S \geq 10^{-9}$	$S < 10^{-9}$

[a] All 1979–1982 data was assigned a confidence value of 2.

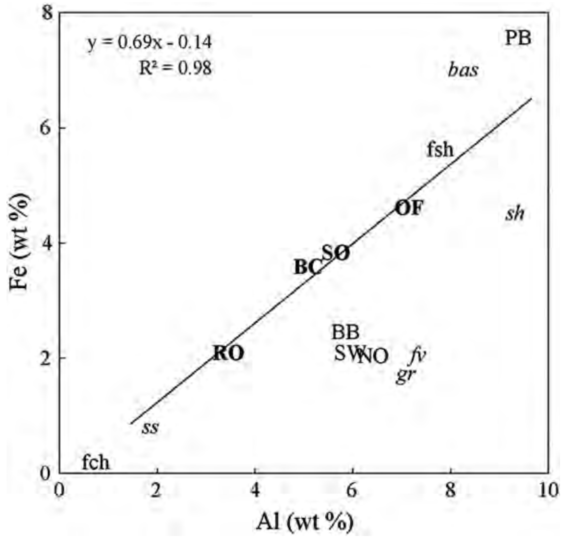

Fig. 9. Iron (Fe) relative to aluminum (Al) contents of sediment at outer coast sites (upper case), Franciscan chert and shale (lower case; Murray et al., 1991), and common rock types (italics; Condie, 1993). Line shows the least-squares regression of four outer coast sites (bold). See Fig. 2 for sample locations. (RO = Rodeo Beach, BC = Bonita Cove, SO = southern Ocean Beach, OF = offshore of southern Ocean Beach, PB = Point Bonita, BB = Baker Beach, SW = sand wave field, NO = northern Ocean Beach, fch = Franciscan chert, fsh = Franciscan shale, ss = sandstone, gr = granite, fv = felsic volcanic, sh = shale, bas = basalt).

of the cells in South, Central, and North Bays, respectively, falling within the same ±90 degree window. Inferred transport patterns west of the Golden Gate are consistent with ebb-dominated flow patterns with sediments traveling in a southwesterly direction through the mouth and over the ebb-tidal delta.

Sediment transport within San Francisco Bay is very complex, and the relatively poor performance of grain size in predicting transport direction is likely due to the numerous limitations and uncertainties of this approach (see Poizot et al., 2008). A fundamental concern is whether the grain size variability captured is associated with a modification of the hydrodynamic energy or with sediment reworking processes. Additional input uncertainties stem from sampling depths (ideally capturing only the time-scale of the depositional process of interest), density of the samples, and the duration over which they were collected. Limitations due to model uncertainties of this simplified trend analysis were not quantified, and as a result, only the transport directions for west of the Golden Gate, where results were validated by independent analyses, were incorporated into the synthesis of this larger project. Because of the many limitations associated with this analysis, all transport directions inferred from grain-size measurements were assigned a low confidence rating.

4.3. Geochemical analyses

4.3.1. Isotopes and rare earth elements

The normalized $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, and Nd/Sr isotope ratios and to a lesser extent the total amounts and ratios of trace and rare earth elements (REE) and high field strength elements (HFSE, such as Y, Zr, Nb, Ta), were used to infer beach-sized sand transport pathways in the region. The Nd and Sr isotope ratios indicate that the sediment within the San Francisco Bay Coastal System can be complexly sourced both locally and distally (Fig. 11). Based on the most robust isotopic indicator (ε_{Nd} — for more information see Rosenbauer et al., 2013–this issue), the predominant source of beach-sized sand to Suisun Bay, San Pablo Bay, and Central Bay is likely derived from the Sierras via the Sacramento River with additional local contributions to San Pablo Bay from the Napa River. The REE data also imply that some sediment is introduced

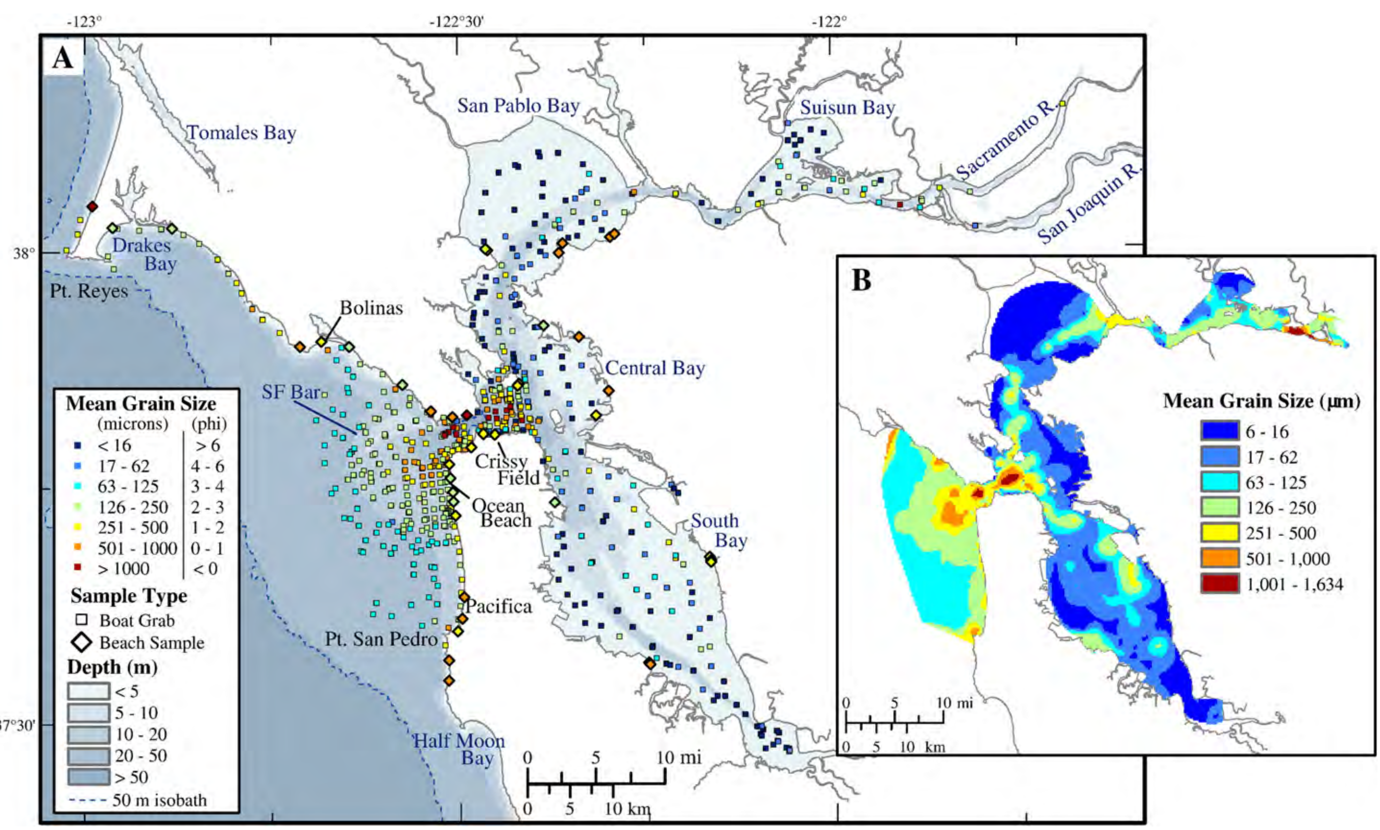

Fig. 10. A) Mean grain size of surface sediment samples, and B) interpolated surface of mean grain size.

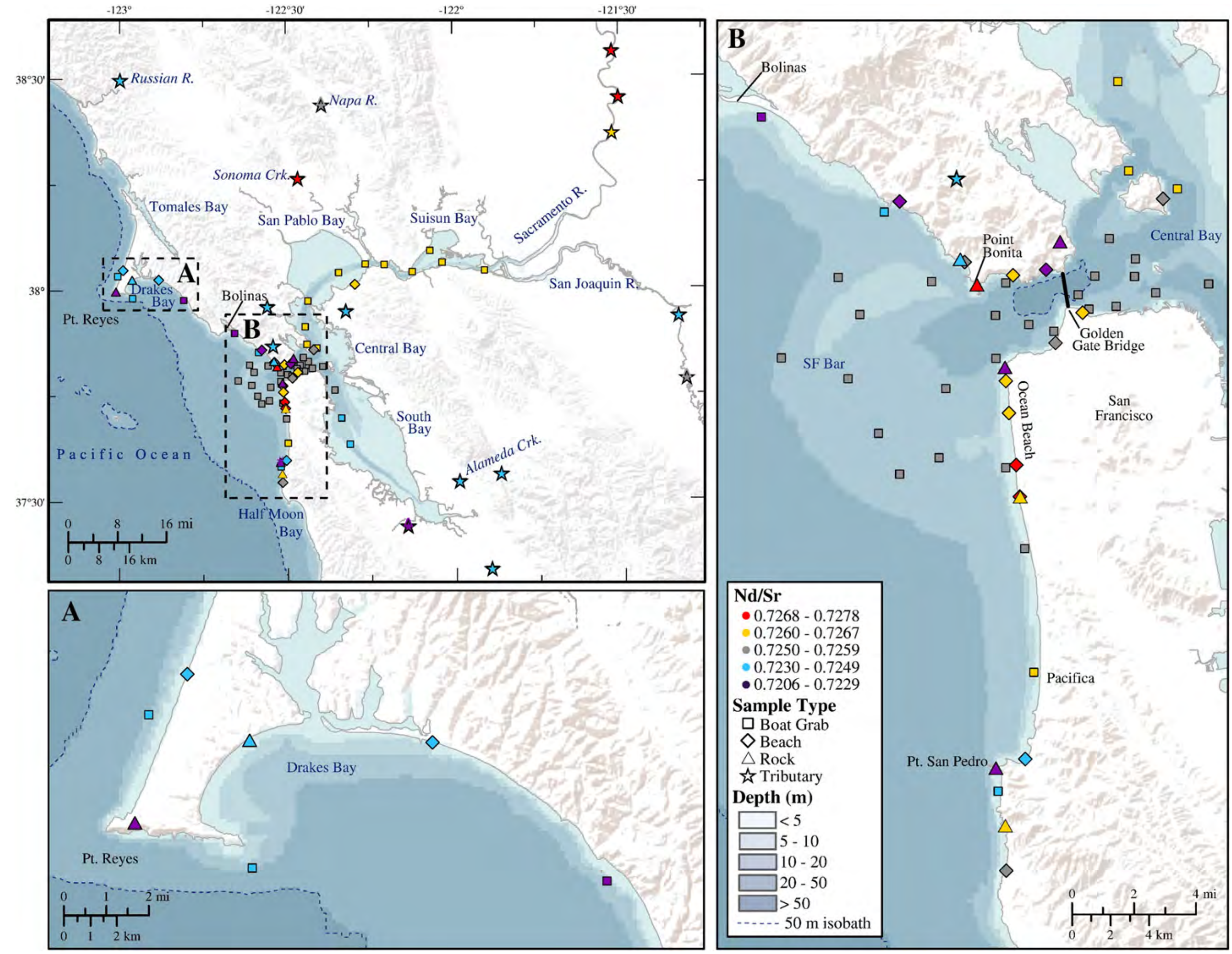

Fig. 11. Nd:Sr isotopic composition ratio of samples (Rosenbauer et al., 2013–this issue).

into Suisun Bay and San Pablo Bay from the San Joaquin River (Fig. 12). Based on the isotopic signatures, some component of sand-sized sediment exits San Francisco Bay proper and is then carried southward along the outer coast by prevailing currents. Nd/Sr isotopic ratios also reveal regions of localized sediment accumulation such as basalt being uniquely deposited around the Golden Gate Bridge. The sandy sediment in the southern half of South Bay is derived from local tributaries, primarily Alameda Creek, with no sediment evident from the Sacramento or San Joaquin Rivers.

On the outer coast of Pt. Reyes north of the Golden Gate Bridge, beach-sized material may in part be derived from the discharge of the Russian River with additional contributions likely from local streams and sandstone outcrops. On the inner coast south of Pt. Reyes there is some material derived from the erosion of the granitic headland that seems contained within Drakes Bay. Most of the sediment on and offshore from Pt. Reyes to the Golden Gate Bridge is consistent with sandstone outcrops at Pt. Reyes and likely other locally-derived geochemically-similar material along the northern open coast. This material mixes with sediment transiting the Golden Gate from within the Bay and some of this material is carried back into Central Bay and partly into South Bay through tidal currents, and some transported southward along and onto Ocean Beach. The beach and offshore sands along the coast south of the Golden Gate are an amalgamation of material transported alongshore from north of the Golden Gate mixed with sediment derived from within the Bay, primarily from the Sacramento River, as well as material derived from local outcrops and creeks (Rosenbauer et al., 2013–this issue). Distinct transport pathways were not discernible from the REE results alone, but aided in interpretation of the isotopic data.

4.3.2. Heavy minerals

Samples from beaches, seafloor, local drainages and cliff outcrops are grouped into two major and three minor classes on the basis of cluster analysis of the heavy mineral abundance (Fig. 13). Twenty-two of the 42 samples fall into class 1 (Sierran), which is characterized by hornblende, hypersthene, and zircon, and occurs throughout the estuary west of Carquinez Strait, through the Golden Gate and southward along the coast. Class 2 (Golden Gate) consists of six samples and is similar to class 1, but has far less hypersthene, more zircon, and a more restricted geography near the Golden Gate. The remaining 14 samples are in geographically restricted areas (Franciscan, Bay streams, and Marin classes) or are outliers unrelated to any other samples. The wide distribution of samples from class 1 indicates that the sand is present throughout the estuary and out of the Golden Gate, but no directional trend is evident in either the abundance of the individual minerals or the weighting from the cluster analysis (Wong et al., 2013–this issue).

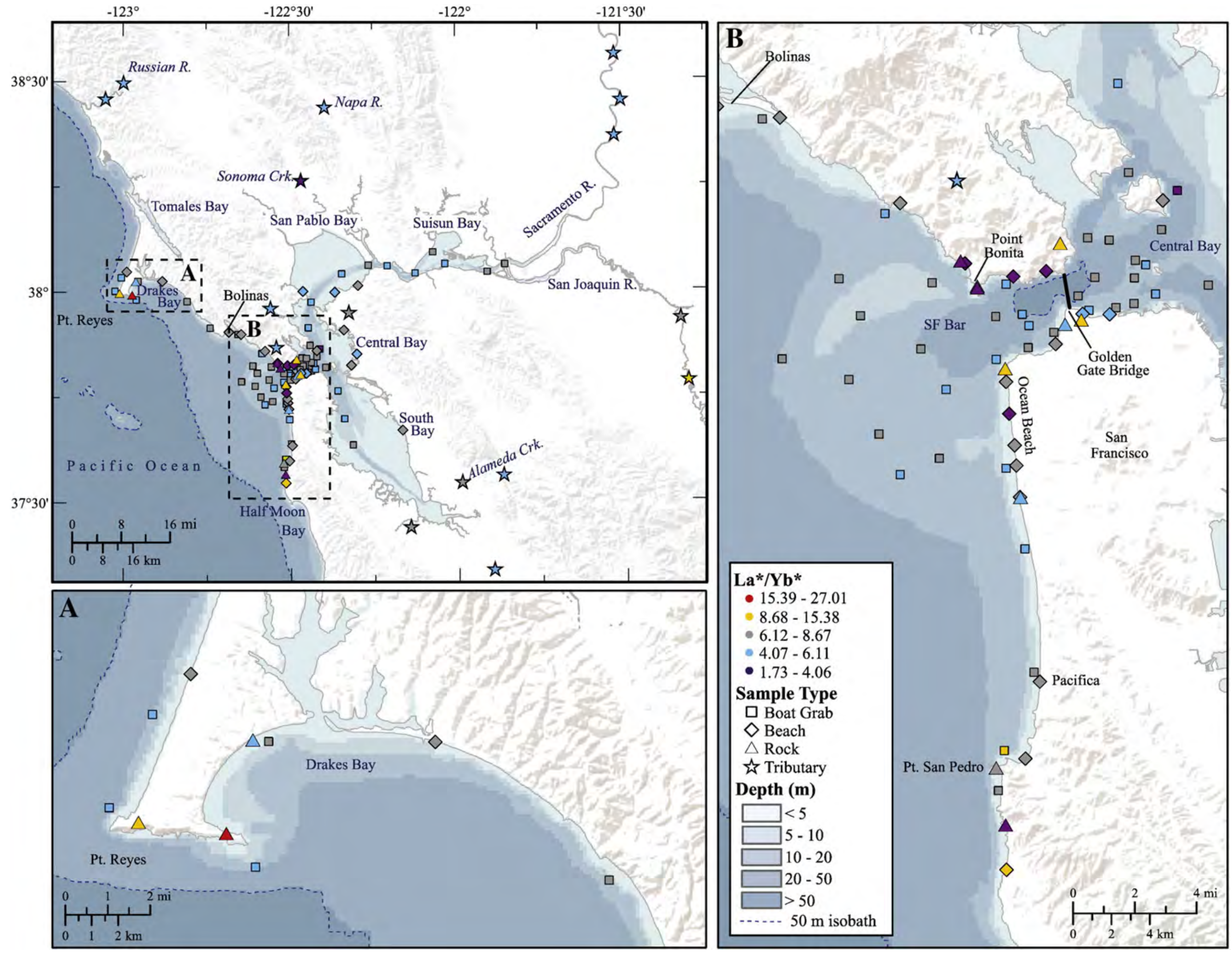

Fig. 12. Representative rare earth element (REE) ratio of samples, lanthanum (La):ytterbium (Yb) (Rosenbauer et al., 2013–this issue).

4.3.3. Semi-quantitative X-ray diffraction bulk sand mineralogy

Beach and offshore sands north of the Golden Gate are derived predominantly from Franciscan rocks eroded by local streams and by the larger Russian River. Sediment from the Russian River moves south along the coast and around Point Reyes (Fig. 14). Rock outcrops provide sources for a component of sand for local beaches and nearshore samples, but are diluted with other sources from longshore transport. The general sediment signature north of the Golden Gate can be traced into Central Bay and across the Bay mouth to the south. Most beach and offshore sands south of the Golden Gate are derived from local outcrops and creeks, longshore transport from north of the Golden Gate, and sediment from the Sacramento and San Joaquin Rivers that transits through San Francisco Bay. Local sources or more distant sources can dominate at any particular beach south of the Golden Gate.

The area around the Golden Gate Bridge is a zone of mixing of sediment from various sources including longshore transport from north of the Golden Gate, westward transport from the Sacramento–San Joaquin and Napa–Sonoma drainages, and northward transport from the area of north Ocean Beach into the southern Bay mouth along Crissy Field. Local sources are prominent for beaches along the Marin Headlands. Beaches just southeast of the Golden Gate receive sand from erosion of local Franciscan sandstone, mixed sediment of the Sacramento–San Joaquin Rivers, and the coast north of the Golden Gate, and from Ocean Beach. The remainder of San Francisco Bay receives sediment predominantly from the Sacramento and San Joaquin Rivers. However, sediment from Napa River and Sonoma Creek can be identified in San Pablo Bay and the South Bay area, and likely forms a small component of Central Bay sediment. Local streams flowing into the southernmost portion of South Bay are recognized in nearby sediments. Sediment from Suisun Bay also receives sediment derived from erosion of the Franciscan Complex, perhaps delivered through small creeks (Hein et al., 2013–this issue).

4.4. Biologic, anthropogenic, and volcanic constituents

Organic and inorganic sediment constituents were recovered in 294 samples collected in the San Francisco Bay Coastal System from 1995 to 2010. Both naturally-occurring and displaced remains are used to identify pathways of sediment transport and sites of deposition in the region (Fig. 15). Offshore water commonly intrudes into Central Bay, to the southern end of South Bay and the middle of San Pablo Bay, and occasionally as far east as Suisun Bay, as evidenced by the presence of marine-indicating organisms such as benthic and planktic foraminifera, ostracods, diatoms, and radiolaria. In contrast, estuarine waters flow from San Francisco Bay out onto the San Francisco Bar and along the coast, as demonstrated by the recovery of estuarine ostracods and benthic foraminifera in nearshore marine

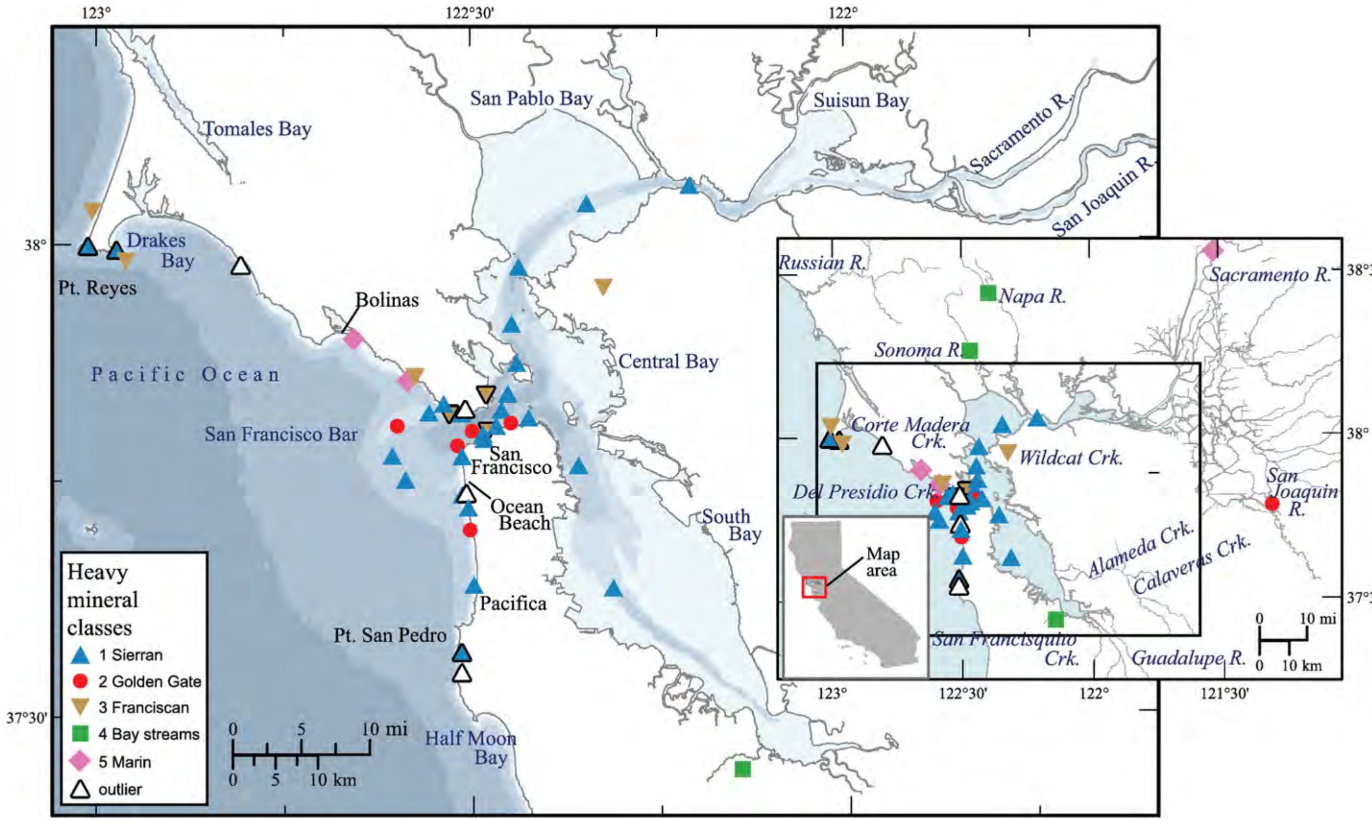

Fig. 13. Distribution of primary heavy mineral classes as determined by cluster analysis. Symbols for cliff rock samples that can be assigned to classes of unconsolidated sediment are outlined in black (Wong et al., 2013–this issue).

samples. Biota which inhabits the periphery of the Bay, such as marsh benthic foraminifera and freshwater gastropods and ostracods, commonly are transported to the middle of the sub-embayments of the estuary. Similarly, terrestrially-derived welding slag and glass microspheres are found in the middle of sub-embayments and outside along the outer coast, far from any docks or roads that are presumed to be their source. Lastly, volcanic glass shards originating from the Sacramento and San Joaquin River watersheds were recovered throughout the Bay, including the extreme end of South Bay and along the open coast south to Pt. San Pedro. From these data, we can conclude that sediment is transported from the Delta to all regions of the Bay and out into the offshore realm, as well as from the marine realm back into San Francisco Bay. The channel in Suisun Bay, San Pablo Bay, Central Bay, and South Bay, and the Golden Gate, are conduits for sediment movement and sites where scouring occurs. However, the transport directions inferred from the biologic, anthropogenic, and volcanic constituents utilized in this portion of the study should be considered with caution, as they are derived from bulk sediment samples, and the hydraulic properties of the constituents considered here are not necessarily consistent with the beach-sized sand fraction isolated for the other techniques. Therefore, while we have used these constituents for supporting evidence in the development of the conceptual sand transport model, we have not included the results with the other eight techniques in the semi-quantitative integration. Nevertheless, this technique clearly demonstrates the well-mixed nature of the estuary, and that fresh, brackish, and marine constituents penetrate into all reaches of the Bay.

4.5. Bedform asymmetry

The mean grain size of bedform sediment samples ranged from 0.014 mm to 1.54 mm (Fig. 10; mean = 0.34 mm, $\sigma = 0.28$), indicating that bedform sediment is a potential source of beach sand, defined here as 0.15–0.50 mm. The direction and degree of bedform asymmetry are indicative of sediment transport direction; bedform asymmetry calculations suggest an ebb-dominated system (Fig. 16), with a mean net ebb asymmetry for the entire system of 5%, and significantly ebb-oriented bedforms at the mouth of San Francisco Bay (11% ebb asymmetry), in San Pablo Bay (7% ebb asymmetry) and Suisun Bay (8% ebb asymmetry). Only South Bay exhibits slight flood-orientation (2% flood asymmetry), while Central Bay exhibits only a slight ebb preference (1% ebb asymmetry). Cross-sections of bedform asymmetry across the narrowest section of Suisun Bay (20% ebb asymmetry), the entirety of Central Bay (12% ebb asymmetry), and the inlet mouth (5% ebb asymmetry) all suggest that the Bay is a net exporter of sand to the open coast. In addition to mean overall ebb orientation of the bedforms, there are a number of large regions where ebb- or flood-directed transport is clearly dominant, such as the southern portion of Central Bay (ebb), through the center of the Golden Gate (ebb), and along the southern margin of the Golden Gate (flood). The asymmetry measurements significantly agree (up to ~76%) with annual residual transport directions derived from numerical modeling (see Section 4.7), and the orientation of adjacent, flow-sculpted seafloor features such as mega-flute structures (Barnard et al., 2013–this issue-a). The complete bedform data are archived at Pangaea (http://dx.doi.org/10.1594/PANGAEA.802345).

4.6. Measured residual currents

Current measurements show that residual currents were predominantly ebb-oriented in the central and northern portions of Suisun Bay (Fig. 17A; Walters and Gartner, 1985; Walters et al., 1985). Measurements in September 1978 showed that during spring tides, a down-estuary flow across the northern portion of Suisun Bay resulted from the tidally-driven residual flow dominating over the density-driven up-estuary flow. During neap tides, the density-driven flow dominated because of decreased

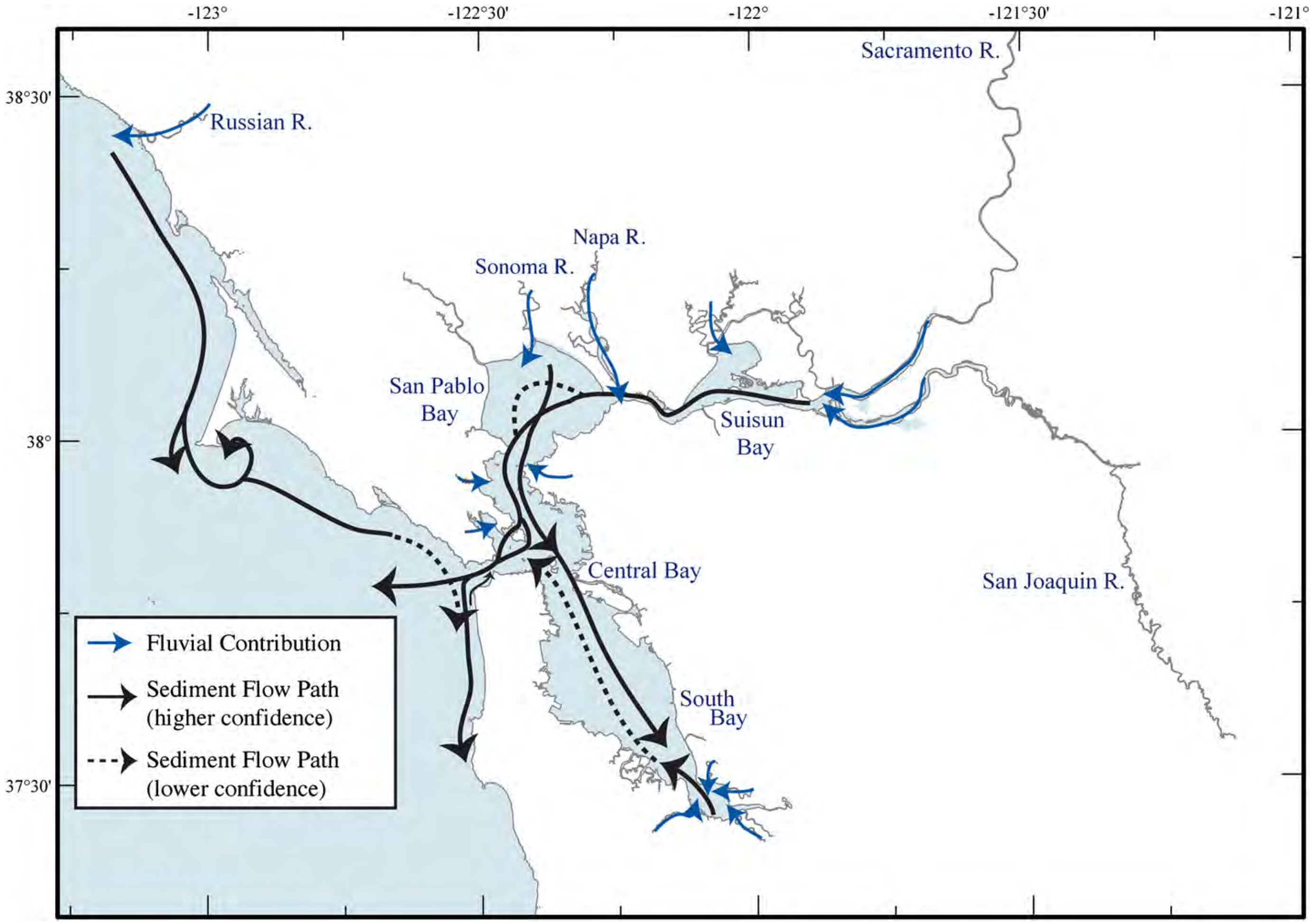

Fig. 14. Summary of beach-sized sand transport pathways based on semi-quantitative X-ray diffraction results. Modified from Hein et al. (2013–this issue).

vertical mixing and weakened residual flow. A comparison of meteorological and current meter data did not reveal any wind-driven component in the residual circulation of Suisun Bay.

In South Bay, measurements obtained with mechanical current meters during the years 1979 to 1982 indicated a residual tidally-driven current northward along the west side of the main channel and eastward along the northern slope of San Bruno shoals (Fig. 17B; Cheng and Gartner, 1985; Walters et al., 1985). Residual flows over the shoals along the eastern part of South Bay were strongly affected by wind-driven currents; under conditions of a north wind, surface flows in the shallow regions were southward with an ebb-directed return flow in the channel. Although these current measurements are ~thirty years old, previous modeling efforts (Gross, 1997) have shown that while winds contribute significantly, tidal currents are the primary forcing responsible for creation of residual circulation in South San Francisco Bay. Unless wind patterns and magnitudes have changed substantially or changes in bathymetry, freshwater loading, and the tidal prism has significantly altered the tidal regime, it is likely that the measurements are still largely representative of circulation in this sub-embayment.

ADP measurements at the two sites along Crissy Field indicate ebb-directed residual currents for both the January and September 2008 deployments (Fig. 17C). Residuals at the westward site were oriented alongshore while at the eastward site (CF2 — near an inlet to a restored tidal wetland), residual currents were ~20° from the shore-normal direction. The shore-normal current component was almost always directed onshore and likely is responsible for the observed sedimentation and frequent closure of the marsh inlet (Hanes et al., 2011). Surface wind stress (Fig. 17D, bottom panel), has a good correlation ($r = 0.65$) with westward- (ebb) directed residual currents, but no correlation with the north–south or shore-normal residual currents. However, the onshore-directed residual currents show a strong ($r = 0.80$) correlation with significant wave heights measured at the San Francisco Bar outside the Golden Gate (Fig. 17D, third panel). The occurrence of large ocean waves has been shown to coincide with marsh closure events (Hanes et al., 2011), further indicating that the ocean swell penetrating through the Golden Gate is largely responsible for the nearshore residual currents and sedimentation along Crissy Field beach.

Along the outer edge of the ebb-tidal delta, residual currents were directed seaward (Fig. 17C). For the winter measurement period in 2006, waves averaged 2.6 m with a maximum of 5.6 m in ~14 m water depth at Site 5, but the depth-averaged residual current (consistently offshore) was poorly correlated with wave height, indicating the dominant influence of the ebb jet emanating from the Golden Gate. Residual current measurements along Ocean Beach (Sites 2, 3 and TV1, 11 m–14 m water depth) showed a consistent north–northwest direction.

4.7. Numerical modeling

Modeled residual transport is dominantly seaward at the mouth of San Francisco Bay, including through the center of the Golden Gate, and across the ebb-tidal delta (Fig. 18). However, there is a narrow but distinct pathway for flood-directed transport from the northern section of Ocean Beach, around Pt. Lobos, and along Baker Beach,

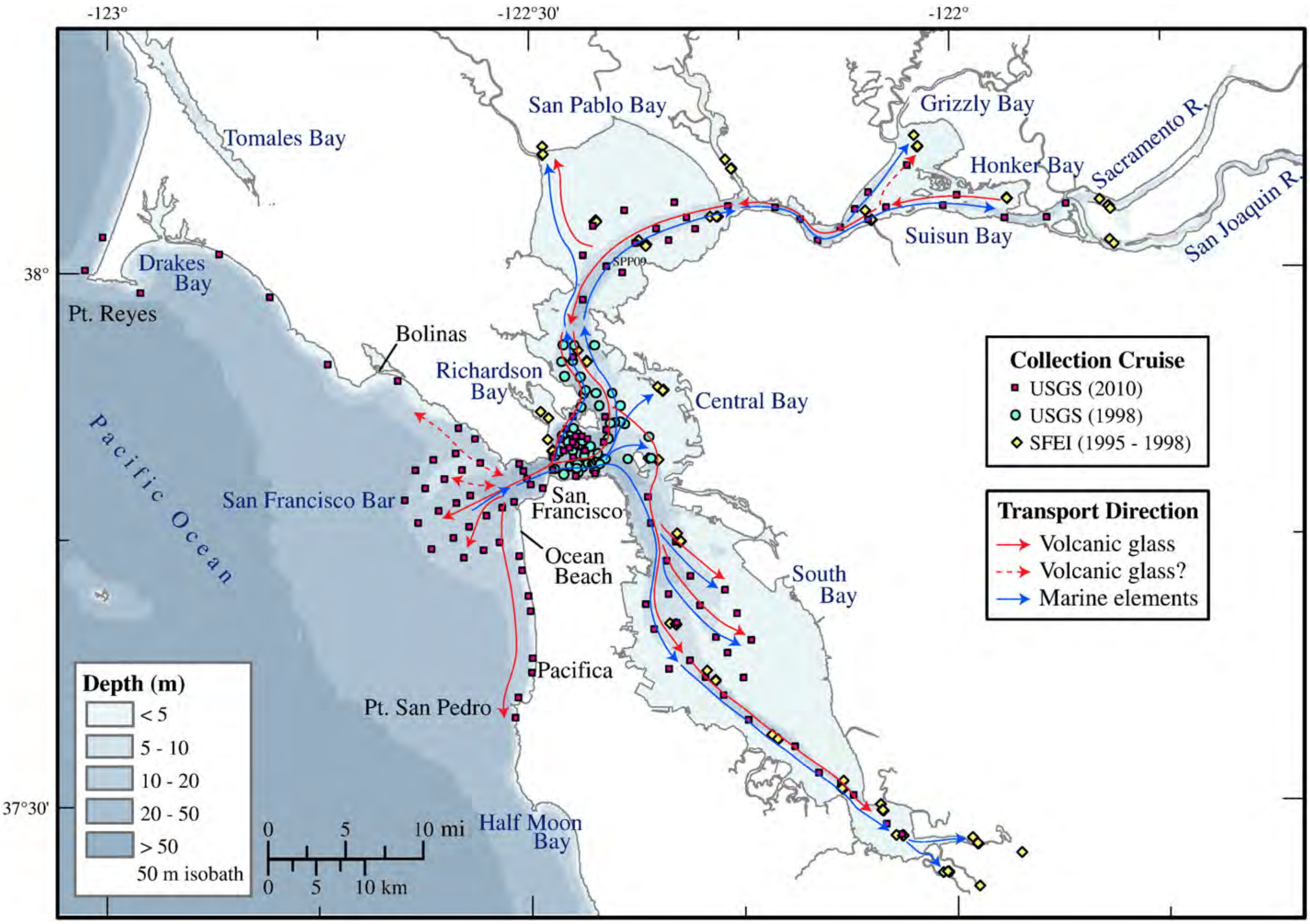

Fig. 15. Location of the sediment constituent study sites and pathways of sediment transport in the San Francisco Bay Coastal System inferred by the presence of marine elements from the offshore realm as well as volcanic glass originating in the Central Valley.
Modified from McGann et al. (2013–this issue).

which also is suggested by many of the other analyses in this paper. Inside Central Bay, ebb-directed transport dominates along the periphery, including the southern and northwest sections. Closer to the Golden Gate strait, flood-directed transport is more prevalent in the center of the inlet, while transport patterns are more complex to the east, but generally agree with the bedform asymmetry patterns for the majority of locations (see Fig. 16). South Bay transport directions are uncertain and often conflict with the other analyses (e.g., only 38% agreement with the bedform asymmetry), but the disagreement is not unexpected as wind-driven gravitational circulation, known to be a key driver of transport patterns in this sub-embayment (Conomos et al., 1985), is not incorporated in the model. Similarly, although modeled transport directions in San Pablo Bay (76% agreement with bedform asymmetry) and to a lesser extent Suisun Bay (65% agreement with bedform asymmetry) are well aligned with the other analyses, the model results are given less weight as density-driven estuarine circulation processes are not simulated and are known to be important in those areas (Monismith et al., 2002).

4.8. Integration of techniques

The consensus beach-sized sand transport directions based on the results for eight of the nine provenance techniques are synthesized in Fig. 19 for each 3×3 km cell. The confidence intervals applied for each technique are listed in Table 4. In the center of the San Francisco Bay Coastal System (i.e., Central Bay, Golden Gate, and ebb-tidal delta), the transport directions and pathways are more robust (i.e., higher confidence: Fig. 19A) and delineated due to the greater sediment sampling density, numerical model calibration and validation, bedform distribution, in situ current measurements, and prevalence of sand-sized material. However, there is substantial regional sampling and geochemical evidence to confidently determine the broad-scale sediment transport pathways throughout the entire system, ranging from the distal sources in the Sacramento, San Joaquin, Napa, and Russian Rivers and Sonoma Creek, through each sub-embayment of the Bay, and along the entire open coast study area.

5. Synthesis and discussion

5.1. Primary sediment sources, sinks and pathways

Through the quantitative integration of eight distinct provenance techniques and guidance from a ninth, the results (Fig. 19) are simplified in a conceptual model of beach-sized sand transport for the San Francisco Bay Coastal System (Fig. 20).

In the northern sub-embayments of San Francisco Bay, Suisun Bay exports sandy sediment to San Pablo Bay, sourced from the Sierras primarily via the Sacramento River, and to a lesser extent the San Joaquin River, in line with previous studies that note the far greater contribution of Sacramento River-derived sediments (Krone, 1979; Porterfield, 1980; Oltmann et al., 1999; Wright and Schoellhamer, 2005). In addition to Sierran sand transported from Suisun Bay, San

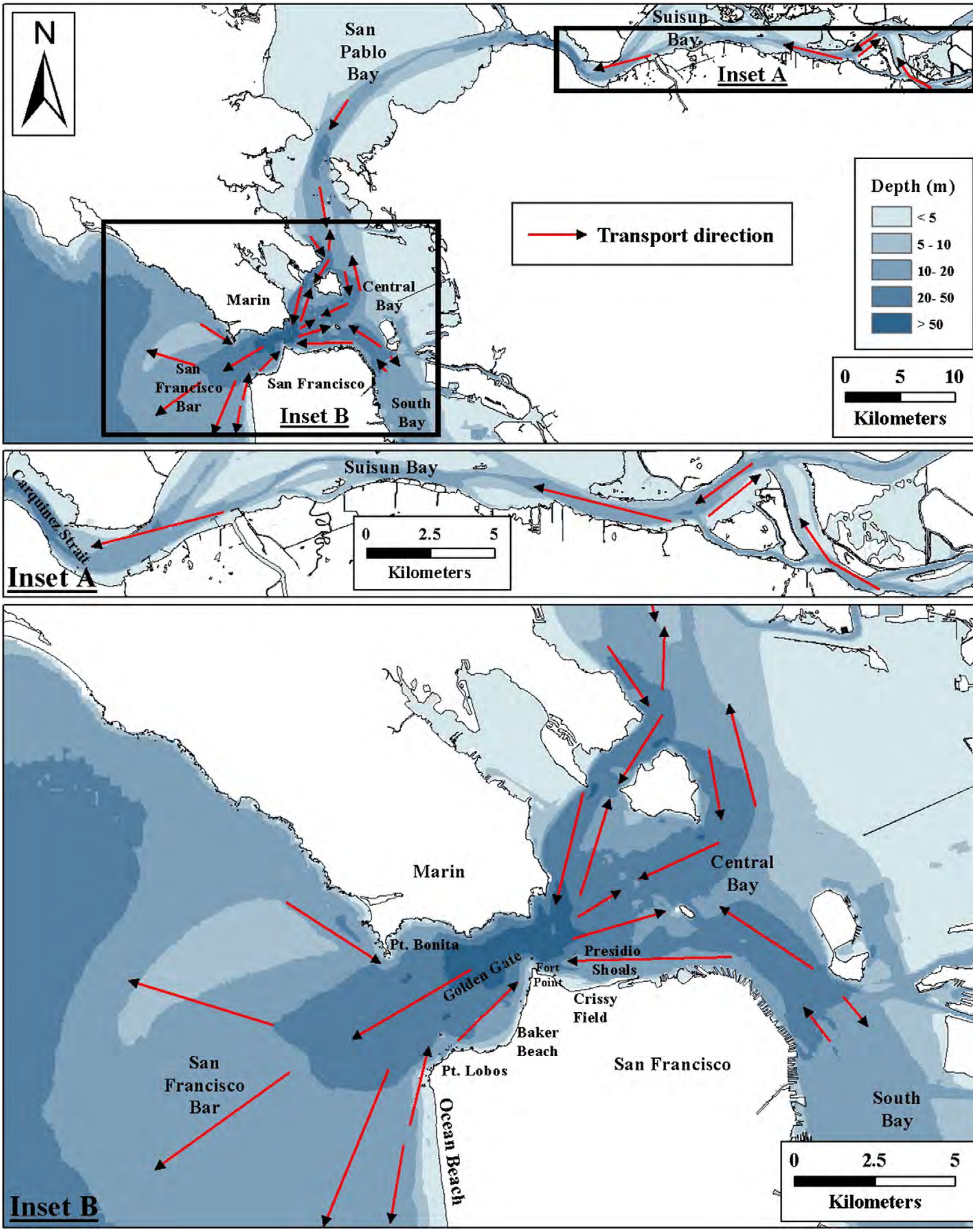

Fig. 16. Inferred sand transport pathways based on agreement between bedform asymmetry and numerical modeling results, simplified from Barnard et al. (2013–this issue-a). Arrow length represents spatial coverage of transport direction agreement.

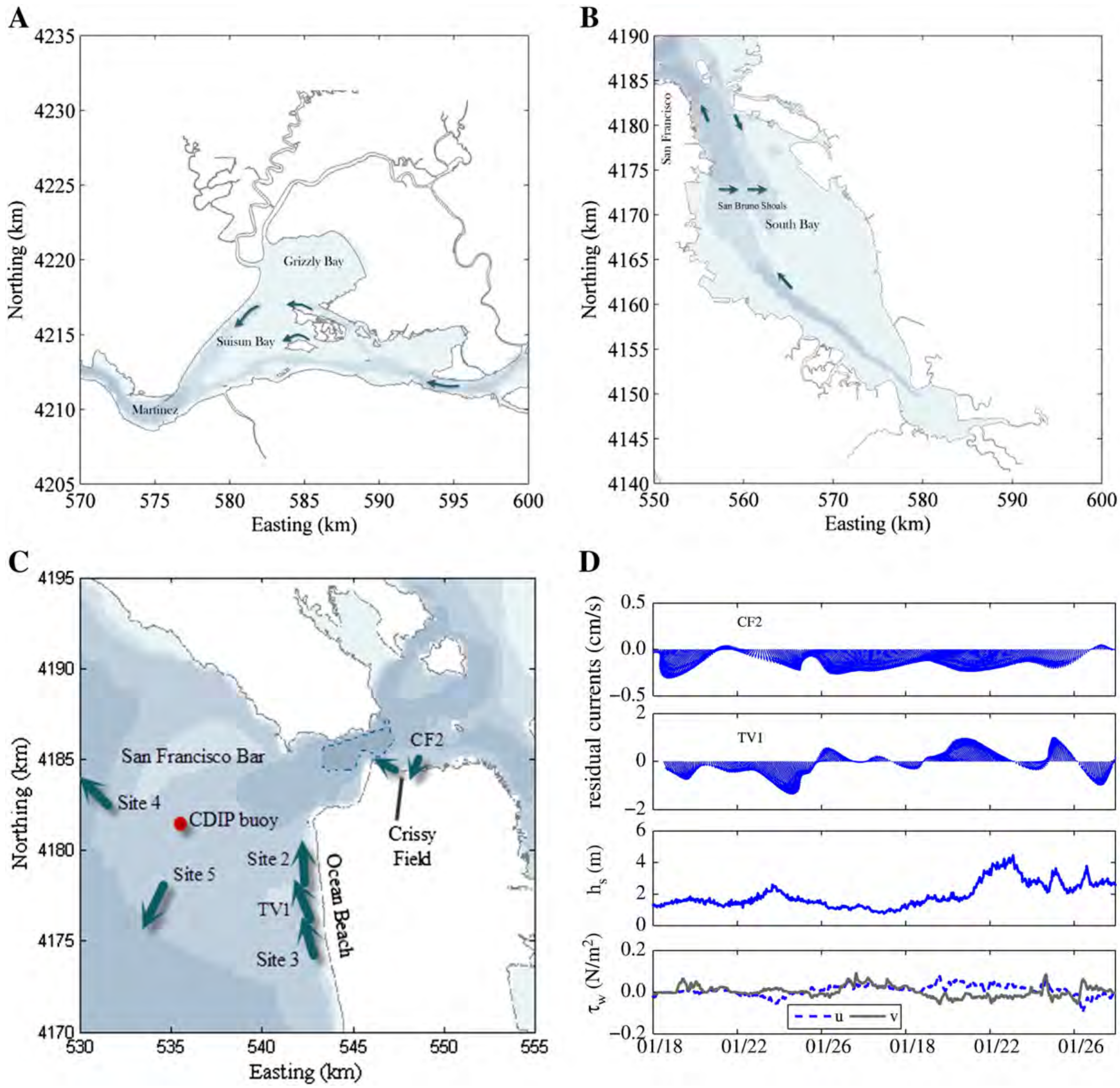

Fig. 17. Depth-averaged residual currents calculated from current measurements in A) Suisun Bay (Walters et al., 1985), B) South Bay (Walters et al., 1985), and C) at the open coast and Crissy Field. Arrow size is not indicative of magnitude or confidence, only direction. Dashed lines show the 50-m isobath. D) Residual currents at CF2 and TV1 (upper 2 panels); third panel — significant wave heights at the San Francisco Bar CDIP buoy; bottom panel — wind stress components calculated using data from the NOAA Ft. Point tide station near CF2 and methods described in Smith (1988).

Pablo Bay receives notable contributions from the Napa and Sonoma drainages, with a net export of sediment to Central Bay. This is the first study that documents sand contributions in the Bay from these two local tributaries, although Porterfield (1980) measured significant quantities of sand in the suspended load (estimate sand transport = ~40 t/day) 10's of kilometers upstream from the Bay outlet of each tributary.

The provenance results demonstrate that South Bay is primarily a sink for beach-sized sand, consistent with the multi-decadal accretionary trend for this sub-embayment (Foxgrover et al., 2004). From the limited number of samples collected within South Bay, it appears that sandy sediment in the southern half of South Bay is derived entirely from local tributaries, particularly Alameda Creek, which is consistent with earlier findings of Conomos (1963). The northern section of South Bay includes sediment derived from both the Central Bay region and the Napa River and Sonoma Creek that enter initially into San Pablo Bay. This is in contrast to the postulation by Gram (1966) that the sand fraction here is entirely locally-derived, and also conflicts with Yancey and Lee (1972) who clearly designate South Bay as a distinct mineral province with sediments derived exclusively from the adjacent tributaries. No evidence of a significant Sierran source in South Bay for beach-sized sand has been detected in the present or prior studies (Conomos, 1963; Gram, 1966; Yancey and Lee, 1972).

Central Bay comprises an amalgamation of sources, but the primary origin of beach-sized sand is from the Sierras via the Sacramento River–Suisun Bay–San Pablo Bay transport pathway, with minor contributions evident from the San Joaquin River, Napa River, Sonoma Creek, local Franciscan sources from the Golden Gate region, and from the open coast north of the Golden Gate. A portion of this sediment is exported to South Bay along the eastern section of the main tidal channel connecting the two sub-embayments, as indicated by bedform asymmetry, current measurements, and XRD. Conversely, along the western end of the channel, South Bay exports sediment

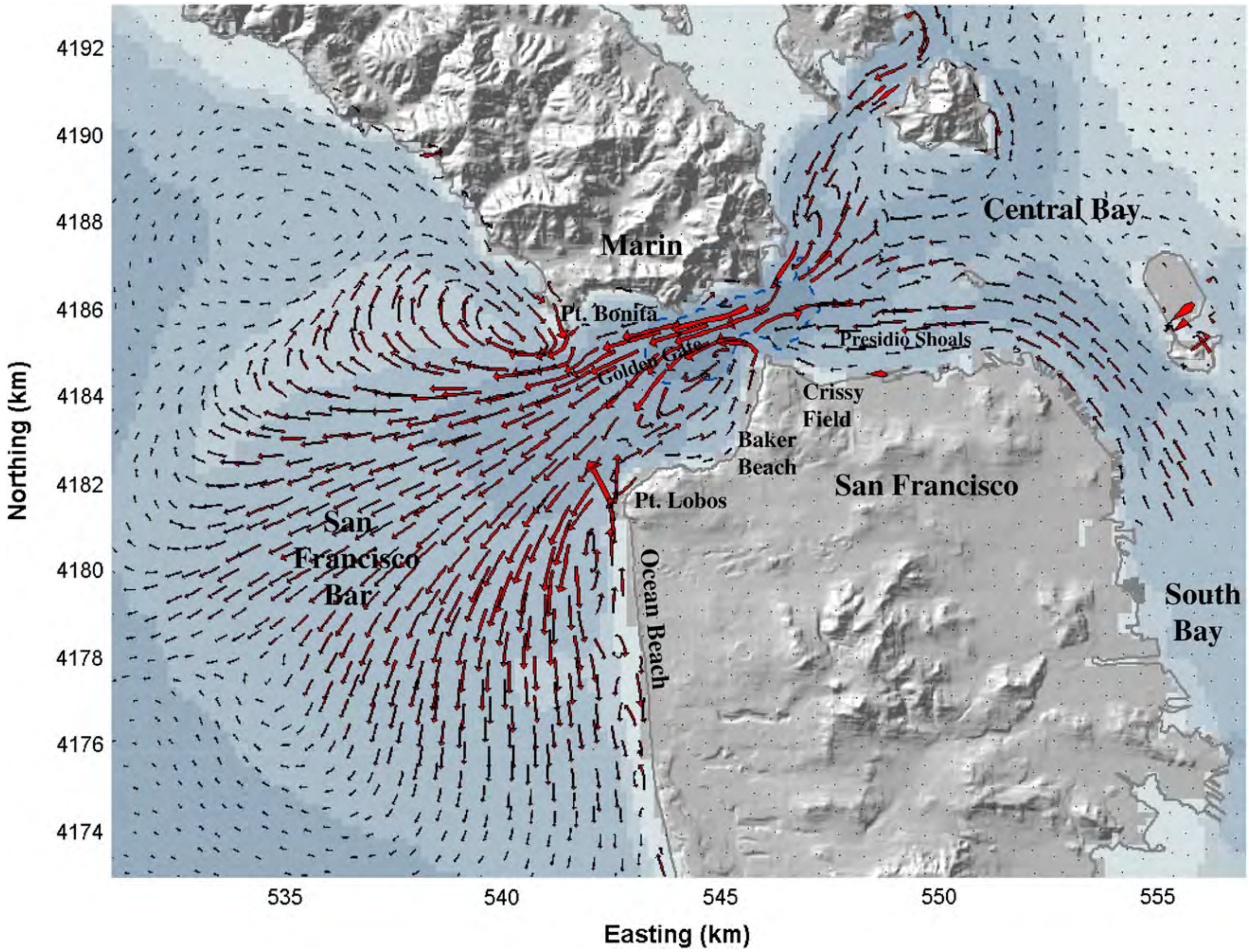

Fig. 18. Modeled residual sediment transport in the San Francisco Bay Coastal System. Axes in UTM coordinate system. Dashed lines show the 50-m isobath. Size of arrows indicates relative magnitude of residual transport.
Modified from Elias and Hansen (2013–this issue).

to Central Bay along a distinct pathway that wraps around the northeastern and northern perimeter of the San Francisco peninsula toward the Golden Gate, clearly delineated through numerical modeling, bedform asymmetry, grain size, current measurements, and XRD.

Beach-sized sand in Central Bay, the Golden Gate, the ebb-tidal delta and southern open coast is strongly geochemically linked. This link is further reinforced by bedform asymmetry, numerical modeling, and current measurements. Through the center of the Golden Gate, net transport is dominantly seaward to the ebb-tidal delta, supported by the highest weighted confidence values in the entire study area. The sediment is derived from numerous locations, most prominently Sierran from the Sacramento River, with additional contributions from the San Joaquin River, Napa River, and Sonoma Creek. Local Franciscan sources are particularly evident on local pocket beaches fed by adjacent outcrops of basalt, chert, and serpentinite. The samples collected from this zone of intense mixing also incorporate sand that moves south via longshore transport from north of the Golden Gate, and northward transport from the area of Ocean Beach, along Baker Beach, and eastward along the northern shoreline of San Francisco (i.e., Crissy Field).

The ebb-tidal delta receives sediment primarily from the Golden Gate (dominantly Sierran), and secondary inputs that move south from the northern coast, derived chiefly from the sandstone outcrops near Pt. Reyes, and more proximal Franciscan outcrops. From the ebb-tidal delta, the majority of sand-sized material moves both alongshore to the south and offshore onto the inner continental shelf.

Along the northern outer coast, sand is derived from the Russian River, particularly north of Pt. Reyes, mixing with granitic and sandstone outcrops near Pt. Reyes, and moving south with additions from Franciscan rocks in cliffs and drained by local streams closer to the Golden Gate. This material moves south by longshore transport, with some material entering Central Bay, possibly around Pt. Bonita, while the rest moves across the ebb-tidal delta toward the southern open coast. The beaches immediately north of the Golden Gate are sourced almost entirely from locally-derived Franciscan outcrops of chert, basalt, and shale.

Beach and nearshore sediment along the southern open coast represents a complex mixture of sand from the northern coast combined with sediment sourced primarily from the Sacramento River (i.e., Sierran) via the Bay, as well as material derived from local outcrops and creeks, with the source contributions varying with alongshore location. Sediment found at northern Ocean Beach is linked geochemically to Baker Beach (and the adjacent Golden Gate sand wave field), and Crissy Field, representative of the dominant Sierran source, and consistent with the geochemistry, numerical modeling, in situ measurements, and bedform asymmetry that document a distinct pathway for sediment into San Francisco Bay along the northern shoreline of the San Francisco peninsula. However, sand at southern Ocean

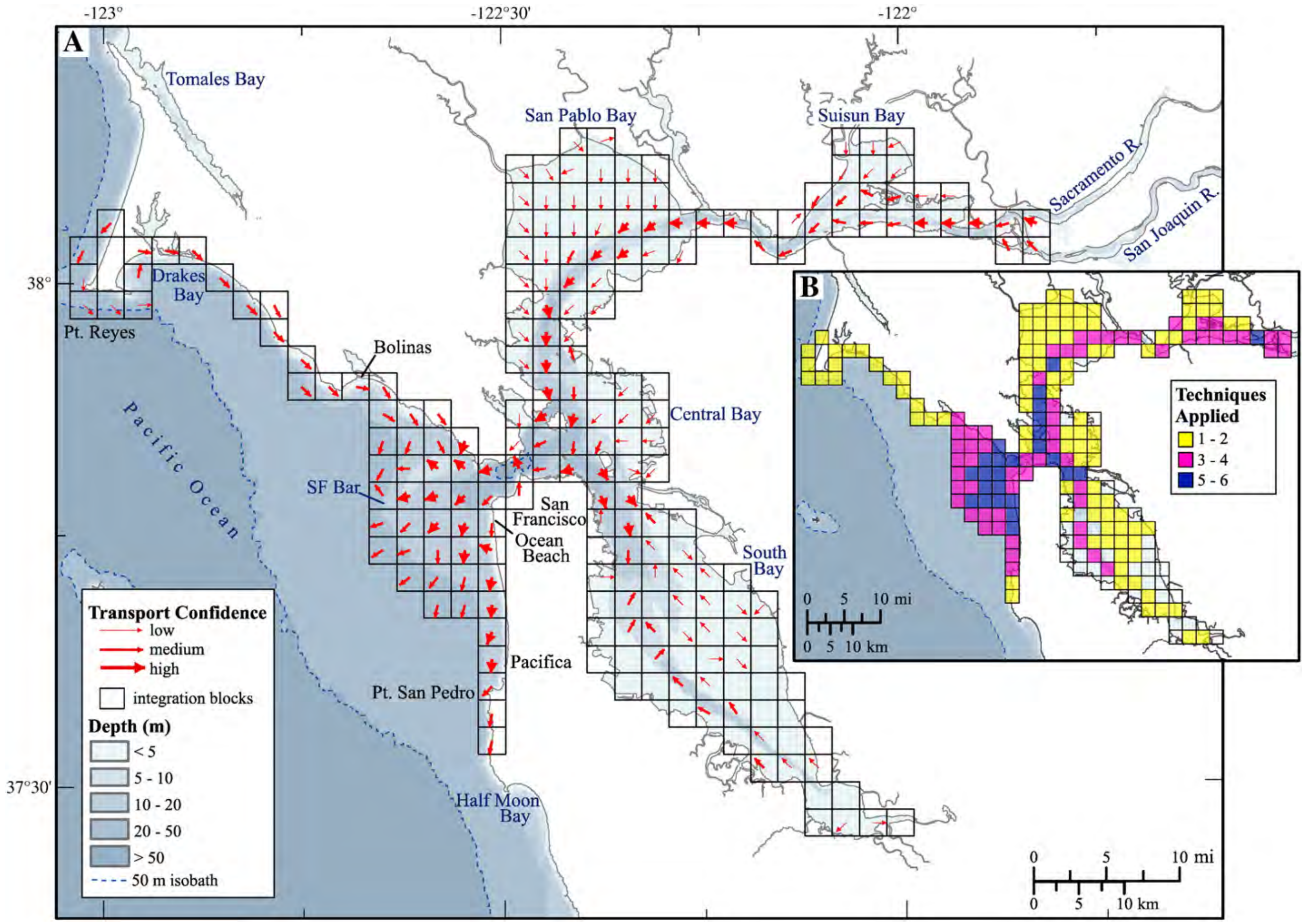

Fig. 19. A) Calculated transport directions based on the integration of the provenance techniques. B) Number of techniques applied for each grid cell to determine the final transport directions.

Beach and offshore are consistent with sand locally eroded from beach-backing cliffs comprising the Colma Formation, distinguished by relatively high magnetite concentrations.

5.2. Implications for regional sediment management

From the above assimilation, a suite of distinct and important transport pathways emerge that have significant implications for regional sediment management (Fig. 20).

5.2.1. Sacramento/San Joaquin Rivers (i.e., Sierran source) → Suisun Bay → San Pablo Bay → Central Bay → Golden Gate → ebb-tidal delta → southern open coast and continental shelf (sink)

For the San Francisco Bay Coastal System, based on the multiple techniques for assessing sand provenance described herein, the Sierra Nevada Range is the dominant source of beach-sized sand, which is actively transported into and through the Bay to the mouth of San Francisco Bay, and along the southern open coast, robustly supporting evidence of this source and pathway from earlier studies that looked at different grain sizes (Gilbert, 1917; Moore, 1965; Yancey and Lee, 1972). Clearly, the sharp reduction in sediment supply from the Sierras over the last century (Wright and Schoellhamer, 2004; Ganju et al., 2008; Singer et al., 2008; Schoellhamer, 2011) via the Sacramento and San Joaquin Rivers, due to the cessation of the hydraulic mining signal and major watershed modifications (Gilbert, 1917; Knowles and Cayan, 2004), has had a significant impact on the sediment supply to the entire region. This dominant pathway for beach-sized sand material destined for the open coast directly intersects the two major active aggregate mining regions in San Francisco Bay, Suisun Bay and Central Bay (Hanson et al., 2004). Also within the 20th century, over 200 million m^3 (~170 Mt, assuming a bulk density of 850 kg/m^3 per Porterfield, 1980) of sediment was directly removed from the San Francisco Bay Coastal System through dredging, aggregate mining, and borrow pit mining, including at least 54 million m^3 of sand-sized or coarser sediment from Central Bay (Dallas and Barnard, 2009, 2011). Together, these changes have contributed to ~240 million m^3 of sediment loss to the San Francisco Bay Coastal System in the last fifty years, as estimated from bathymetric change surveys (Capiella et al., 1999; Foxgrover et al., 2004; Jaffe and Foxgrover, 2006; Hanes and Barnard, 2007; Jaffe et al., 2007; Fregoso et al., 2008; Barnard and Kvitek, 2010). Over 150 million m^3 of measured volume loss during this period is from the sand-dominated substrates of Central Bay, the Golden Gate, and ebb-tidal delta (Hanes and Barnard, 2007; Fregoso et al., 2008; Barnard and Kvitek, 2010). Coastal erosion along the outer coast south of the Golden Gate during this same period is the highest for the entire coast of California (Hapke et al., 2006, 2009), and has accelerated by 50% between Ocean Beach and Pt. San Pedro since the 1980s (Dallas and Barnard, 2011). As further evidence of the continued reduction in sediment supply within the system, Schoellhamer (2011) observed a 36% step decrease in suspended sediment concentrations inside the Bay between water years 1991–1998 and 1999–2007. At the mouth of San Francisco Bay, Barnard et al. (2012a) documented a fining of mean

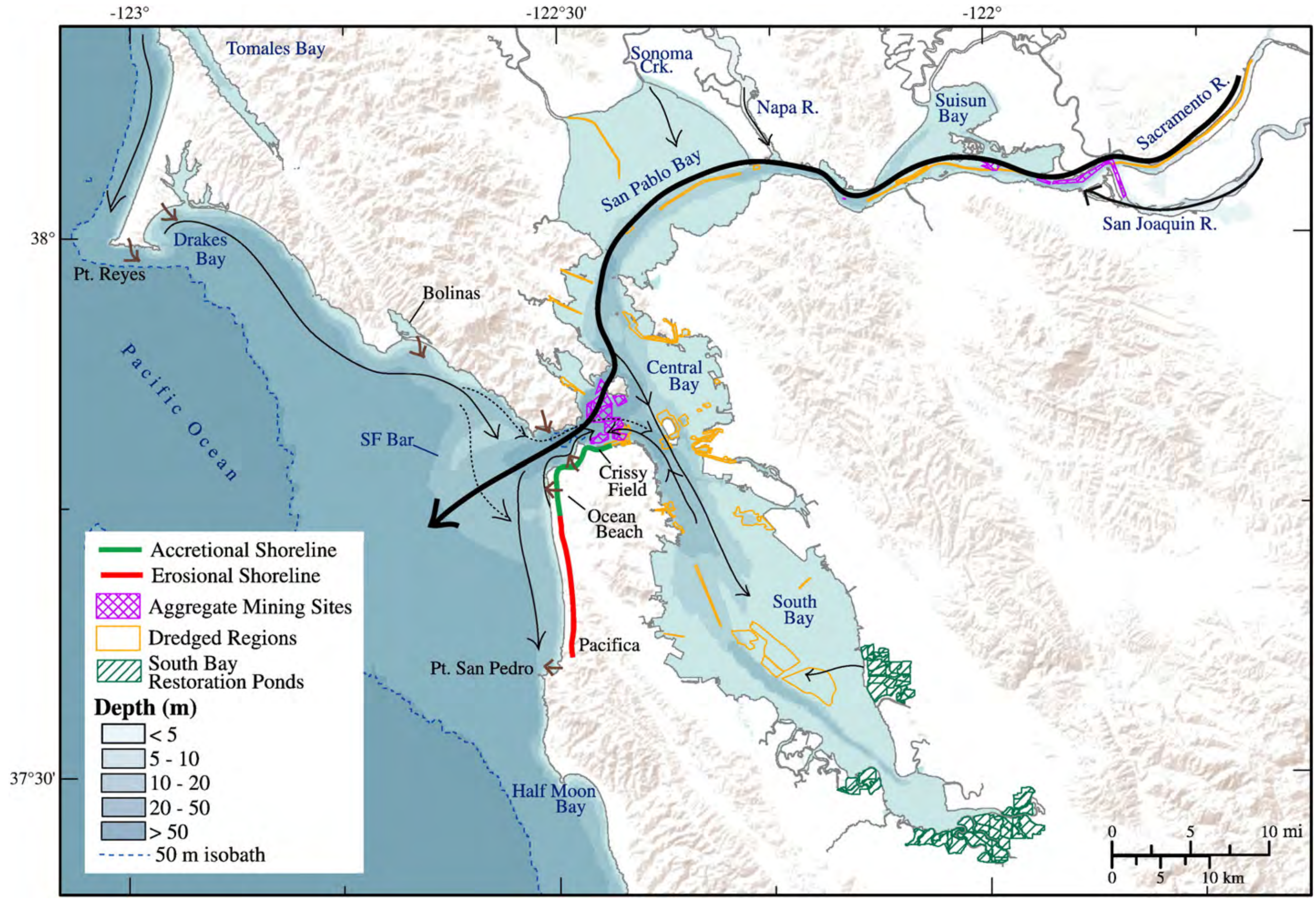

Fig. 20. Final conceptual model of the primary beach-sized sand transport pathways in the San Francisco Bay Coastal System, based on the integration of the provenance techniques. Notable anthropogenic activity locations and significant shoreline change trends are also plotted.

grain size by ~0.025 mm from 1997 to 2008, in particular progressively finer sediment along the outer reaches of the ebb-tidal delta between 2002 and 2007, indicating a reduction in the coarser sand supply.

Looking forward over the next century, the National Research Council (2012) projects 92 cm (range 42–166 cm) of sea level rise by 2100 for San Francisco Bay. Outer coast and Bay beaches, an important line of defense against storm impacts and rising sea levels, will require increasingly higher rates of sand supply to prevent erosion and landward migration, which in many locations would threaten fringing development. Using Global Climate Models linked to regional physical and ecological models in the San Francisco Bay area through 2100, Cloern et al. (2011) projected reduced fluvial discharge from the Sacramento–San Joaquin Delta, a further decline in suspended sediment concentration, and a marked increase in the frequency of extreme water levels. At present, aggregate mining removes approximately 0.9 million m^3/yr of sand and gravel-sized sediment in Central Bay and Suisun Bay (Hanson et al., 2004), while dredging removes about 3 million m^3/yr of sediment, with the majority of this material permanently removed from the San Francisco Bay Coastal System (Dredged Material Management Office, 2008; Keller, 2009; San Francisco Estuary Institute, 2009). Together, these losses exceed the present annual sediment supply from the Sierras and local watersheds combined (Schoellhamer et al., 2005; McKee et al., 2013–this issue). Therefore, management of the current sediment inventory in the Bay will be critical.

5.2.2. Ocean Beach → Baker Beach → Crissy Field

Multi-decadal erosion and contraction of the ebb-tidal delta (Hanes and Barnard, 2007; Dallas and Barnard, 2011) have modified sediment transport patterns along Ocean Beach, effectively driving more sediment toward the northern end of the beach and less toward the southern end (Hansen et al., 2013–this issue). The modeled patterns are supported by observed beach and nearshore changes over interannual (Hansen and Barnard, 2010) and multi-decadal time scales (Dallas and Barnard, 2011; Barnard et al., 2012a), including an ~3 fold increase in the rates of shoreline accretion at the north end over the last several decades, and similarly higher rates of erosion at the south end that have led to significant infrastructure damage (Barnard et al., 2011a). As the northern shoreline has continued to extend seaward, increasingly higher volumes of northward-moving sand are no longer trapped by Pt. Lobos at the north end of Ocean Beach, and instead move toward Baker Beach and eventually into Central Bay at Crissy Field (Fig. 20). For example, over the last decade, sedimentation forced the relocation of a tide gauge and caused shoaling within the adjacent yacht harbor. These three sites have now been linked geochemically in this study, and recently accelerating rates of shoreline accretion at Baker Beach and Crissy Field correlate temporally with observed changes at northern Ocean Beach (Dallas and Barnard, 2011). These trends and correlative impacts are expected to continue (Hansen et al., 2013–this issue) as higher sea levels and further reductions in sediment supply drive further contraction of the ebb-tidal delta.

5.2.3. Northwest South Bay → southern Central Bay → Golden Gate

This distinct pathway, substantiated by a wide range of provenance techniques (i.e., XRD, bedform asymmetry, current residuals, numerical modeling), intersects three lease sites on Presidio Shoals in southern Central Bay (see Figs. 18, 20), where active aggregate mining takes place (Fig. 20). Bathymetric change analysis from 1997 to 2008 across the lease sites records a volume loss of ~2.3 million m^3; most of this attributed to sand and gravel removal by aggregate mining (Barnard and Kvitek, 2010), significantly reducing the sediment available for transport to the mouth of San Francisco Bay and adjacent beaches.

5.2.4. South Bay local tributaries (source) → South Bay (sink)

The integrated provenance results demonstrate that South Bay is primarily a sink of beach-sized sand (with the notable exception of the northwest portion as described in the previous section), particularly the southern half, where local tributaries, namely Alameda Creek and its tributary, Calaveras Creek, are the primary sources, with no evidence of a Sierran component. As South Bay is the only sub-embayment with a recent accretionary trend (Foxgrover et al., 2004), and is the site for the largest tidal wetland restoration on the west coast, the prospects that the newly created tidal wetlands will keep up with sea level rise are greater than for regions that rely directly on a Sierran source where sand supply continues to trend downward.

5.2.5. Russian River (source) → Pt. Reyes → ebb-tidal delta → southern open coast (sink)

In contrast to earlier analyses of heavy minerals contained in beach and inner shelf sediments that suggested that the Russian River was not a major source of sediment in the vicinity of Pt. Reyes south to the Golden Gate (Cherry, 1964; Minard, 1971; Demirpolat, 1991), the geochemical evidence here links the Russian River-derived sand to beach sand immediately north of Pt. Reyes. XRD analyses further suggest that the Russian River influence may extend as far downcoast as the ebb-tidal delta and southern open coast. It is possible that the finer sand grain sizes (<0.25 mm heavy minerals) in the prior studies would have been more easily advected offshore at the Russian River mouth and at Bodega Head, effectively removing them from the littoral system, although the density of these heavy minerals would make them more hydraulically comparable to coarser, more commonly-occurring beach mineral grains. Nevertheless, depending on the impact of future climate change on Russian River discharge rates, this source may help to mitigate coastal erosion pressures on outer coast beaches driven by rising sea levels and the projected continued reduction in the Sierran sediment supply.

6. Conclusions

Through the unique integration of nine separate provenance techniques, the sources and pathways for beach-sized sand in a complex coastal–estuarine system have been robustly established. The consensus results highlight the regional impact of a sharp reduction in the primary sediment source to the San Francisco Bay Coastal System over the last century – the Sierras – in driving massive erosion of the Bay floor, ebb-tidal delta, and the highest regional shoreline retreat rates in California along the adjacent outer coast. In addition, this work also highlights the need to more efficiently manage existing in-Bay sediment resources, as active aggregate mining and dredging occurs along well-defined sand transport pathways that carry sediment toward outer coast beaches, at removal rates that exceed the present-day sediment supply rates from all San Francisco Bay watersheds. Given the observed reduction in contributions from the Delta, and the relative increase of the sediment supply from local tributaries which may be enhanced in the coming decades due to flood control strategies within local watersheds, future beach-sized sand provenance should evolve over the course of the next century to represent these more proximal sources. The comprehensive approach introduced here also definitively established other, previously unresolved secondary sources of sand input to the system that may contribute to the sustainability of beaches on a local and system-wide scale, including the Russian and Napa Rivers, and eroding cliff and bluff sources, such as in the vicinity of Pt. Reyes, within and adjacent to the Golden Gate (e.g., Franciscan Formation), and along the southern open coast (e.g., Colma Formation). Cross-validating geochemical analyses, numerical modeling, physical process measurements, and proxy-based techniques (e.g., bedform asymmetry, grain size morphometrics) is an effective approach for confidently defining sources, pathways and sinks of sand in complex coastal–estuarine systems.

Acknowledgements

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Supplementary data

The grain size, geochemical, and biologic, anthropogenic, and volcanic constituents data are permanently archived at Pangaea: http://dx.doi.org/10.1594/PANGAEA.803904. The bedform data can also be found at Pangaea (http://dx.doi.org/10.1594/PANGAEA.802345).

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Exhibit E

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Sediment transport in the San Francisco Bay Coastal System: An overview

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ABSTRACT

The papers in this special issue feature state-of-the-art approaches to understanding the physical processes related to sediment transport and geomorphology of complex coastal–estuarine systems. Here we focus on the San Francisco Bay Coastal System, extending from the lower San Joaquin–Sacramento Delta, through the Bay, and along the adjacent outer Pacific Coast. San Francisco Bay is an urbanized estuary that is impacted by numerous anthropogenic activities common to many large estuaries, including a mining legacy, channel dredging, aggregate mining, reservoirs, freshwater diversion, watershed modifications, urban run-off, ship traffic, exotic species introductions, land reclamation, and wetland restoration. The Golden Gate strait is the sole inlet connecting the Bay to the Pacific Ocean, and serves as the conduit for a tidal flow of ~8×10^9 m^3/day, in addition to the transport of mud, sand, biogenic material, nutrients, and pollutants. Despite this physical, biological and chemical connection, resource management and prior research have often treated the Delta, Bay and adjacent ocean as separate entities, compartmentalized by artificial geographic or political boundaries. The body of work herein presents a comprehensive analysis of system-wide behavior, extending a rich heritage of sediment transport research that dates back to the groundbreaking hydraulic mining-impact research of G.K. Gilbert in the early 20th century.

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1. Introduction

San Francisco Bay (Fig. 1) is the largest estuary on the U.S. West Coast, and the 2nd largest in the United States (Conomos et al., 1985); combined with the contiguous Sacramento–San Joaquin Delta (Fig. 2) it covers a total surface area of ~4100 km^2 and a watershed area of ~162,000 km^2. It contains several economically significant harbors ($20 billion worth of cargo annually) in one of the most developed regions of the United States, with a surrounding population of over seven million people. San Francisco Bay and the adjoining Delta are among the most human-altered estuaries and hydrologic systems, respectively, in the world (Knowles and Cayan, 2004). Major historical changes were driven by the extensive hydraulic mining influx of sediment in the late 19th century (e.g., Gilbert, 1917), massive alteration of the drainages entering San Francisco Bay in the 20th century (e.g., Wright and Schoellhamer, 2004), and the enormous amounts of sediment removed throughout the San Francisco Bay Coastal System from the early part of the 20th century to the present (e.g., Dallas and Barnard, 2011). The system is well-advanced along the timeline of human development common to many estuaries, i.e., disruption (mining, deforestation, agriculture, urbanization) in the watershed that increases load, followed by dams, water diversions, and river management that reduce variability and thus sediment supply, and now restoration of damaged habitats. The many alterations to the system have resulted in significant changes to the Bay floor, area beaches, Bay-fringing tidal marshes, and ecosystems, serving as an example for understanding the evolution of other estuaries. Coupled with strong anthropogenic signals, distinct and powerful natural processes make this region the ideal scientific laboratory for analyzing sediment transport processes, including strong seasonal variability between wet and dry seasons, well-defined flow pulses, strong interannual variability of freshwater inflow, well-defined estuarine boundaries, and strong seasonal variations in wind strength. In addition to the above, intense resource management has provided a critical mass of modern data and studies.

This special issue is a culmination of nearly 100 years of sediment transport research in the San Francisco Bay Coastal System. Here we present ~20 papers, representing the state-of-the-art in sediment transport research on many topics, ranging from tidal marsh sustainability, suspended sediment transport variations, bedform migration and evolution, behavior of the open coast littoral system, and fluvial inputs. The intention of this introductory paper is to describe prior research that forms the basis of our understanding of the fundamental processes that shape this complex coastal–estuarine system, and to clearly identify the data gaps that are addressed in this special issue.

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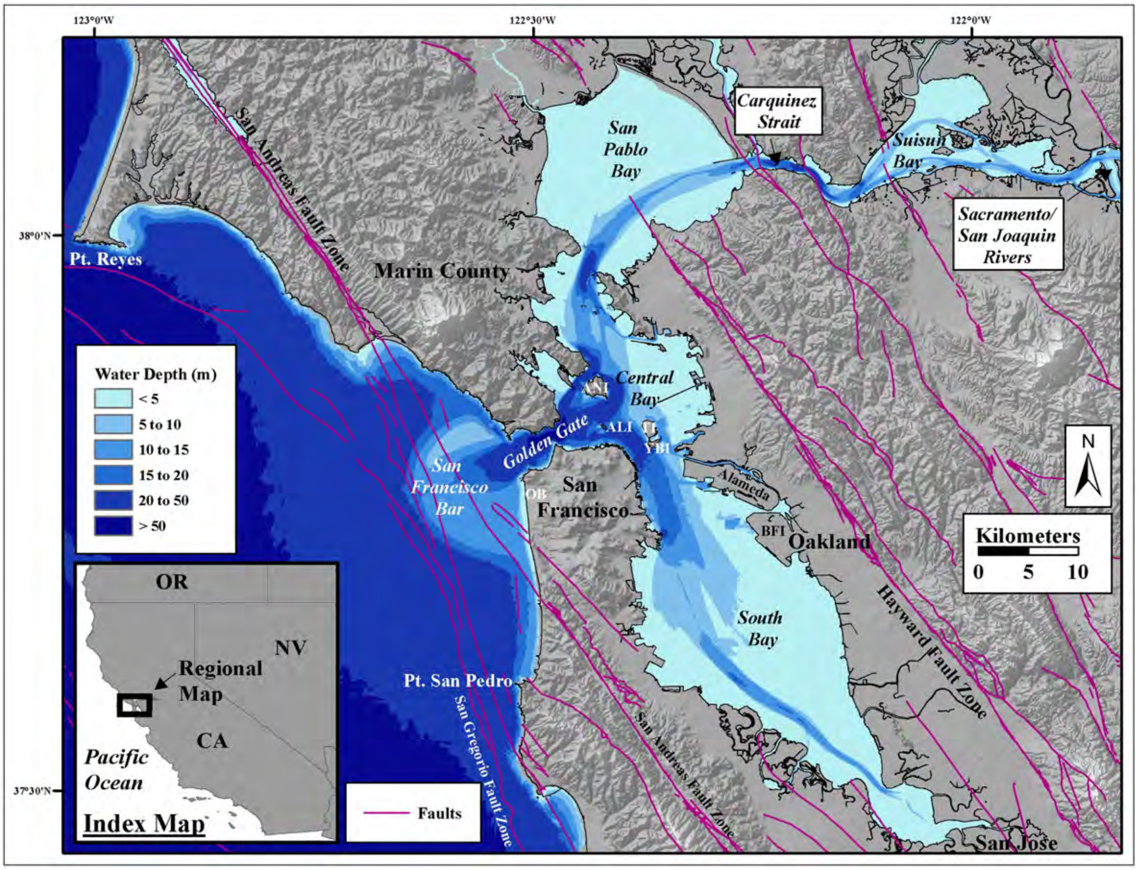

Fig. 1. The San Francisco Bay Coastal System, including major tributaries. Fault lines from U.S. Geological Survey (2006). (ALI = Alcatraz Island, ANI = Angel Island, BFI = Bay Farm Island, OB = Ocean Beach, TI = Treasure Island, YBI = Yerba Buena Island).

Despite the legacy of sediment transport research in the San Francisco Bay Coastal System, there are still some fundamental questions that remain unanswered, which this special issue addresses.

1) What are the primary sediment transport pathways, sources and sinks?
2) How has sediment delivery to the estuary changed over the course of the last century?
3) What is the net direction of sediment transport across the Golden Gate? Is the Bay a net importer or exporter of sand?
4) Is there a geochemical signature that can link sediment inside and outside the Bay?
5) What is the current trend of suspended sediment concentration in the Bay? What are the ramifications of this signal for marsh sustainability as sea level rises during the 21st century?
6) How will current trends in sediment transport dynamics and projected climate change affect the future morphological evolution of the San Francisco Bay Coastal System?
7) How do physical processes and topography control circulation and sediment transport patterns?
8) Can fine sediment transport and morphological evolution be effectively simulated with numerical models?

While this special issue will have direct implications for the regional management of the San Francisco Bay Coastal System, the techniques applied and physical processes analyzed throughout this special issue are on the cutting edge of sediment transport research, and add to the collective knowledge base and understanding of coastal–estuarine systems worldwide.

2. Historical geomorphology and sediment transport

2.1. Early history of San Francisco Bay

San Francisco Bay is situated in a tectonically active basin created from a structural trough that formed during the late Cenozoic (Lawson, 1894, 1914; Atwater et al., 1977; Atwater, 1979). It is bordered by the Hayward Fault Zone to the east and the San Andreas Fault Zone to the west (Fig. 1), which are both associated with the plate transform motion of the San Andreas Fault system (Parsons et al., 2002). The basin has been occupied by an estuary during interglacial periods, and was traversed by a fluvial system during glacial periods, with the current drainage configuration from the Central Valley established by ~0.4–0.6 Ma (Lawson, 1894, 1914; Atwater et al., 1977; Atwater, 1979; Sarna-Wojcicki et al., 1985; Harden, 1998; Lanphere et al., 2004). The open-coast shoreline was located approximately 32 km west of its present position during the Last Glacial Maximum (~18 ka), the current position of the continental shelf break. The basin was most recently flooded during the Early Holocene (Gilbert, 1917; Louderback, 1941, 1951), between 10 ka and 11 ka, as rising sea level inundated the Sacramento River channel that cuts through San Francisco Bay, through the Golden Gate straight, and across the continental shelf (Atwater et al., 1977). Schweikhardt et al. (2010) interpreted the oxygen isotopic composition of foraminifera in a sediment core taken from San Francisco Bay to indicate that the modern estuary was established by 7.7 ka, by 7.4 ka the estuary was highly stratified, and within another century a gradual decrease in water column stratification produced conditions that are similar to the modern, partially-mixed estuary. In the Delta, marshes began forming approximately 6.8 ka, which is likely

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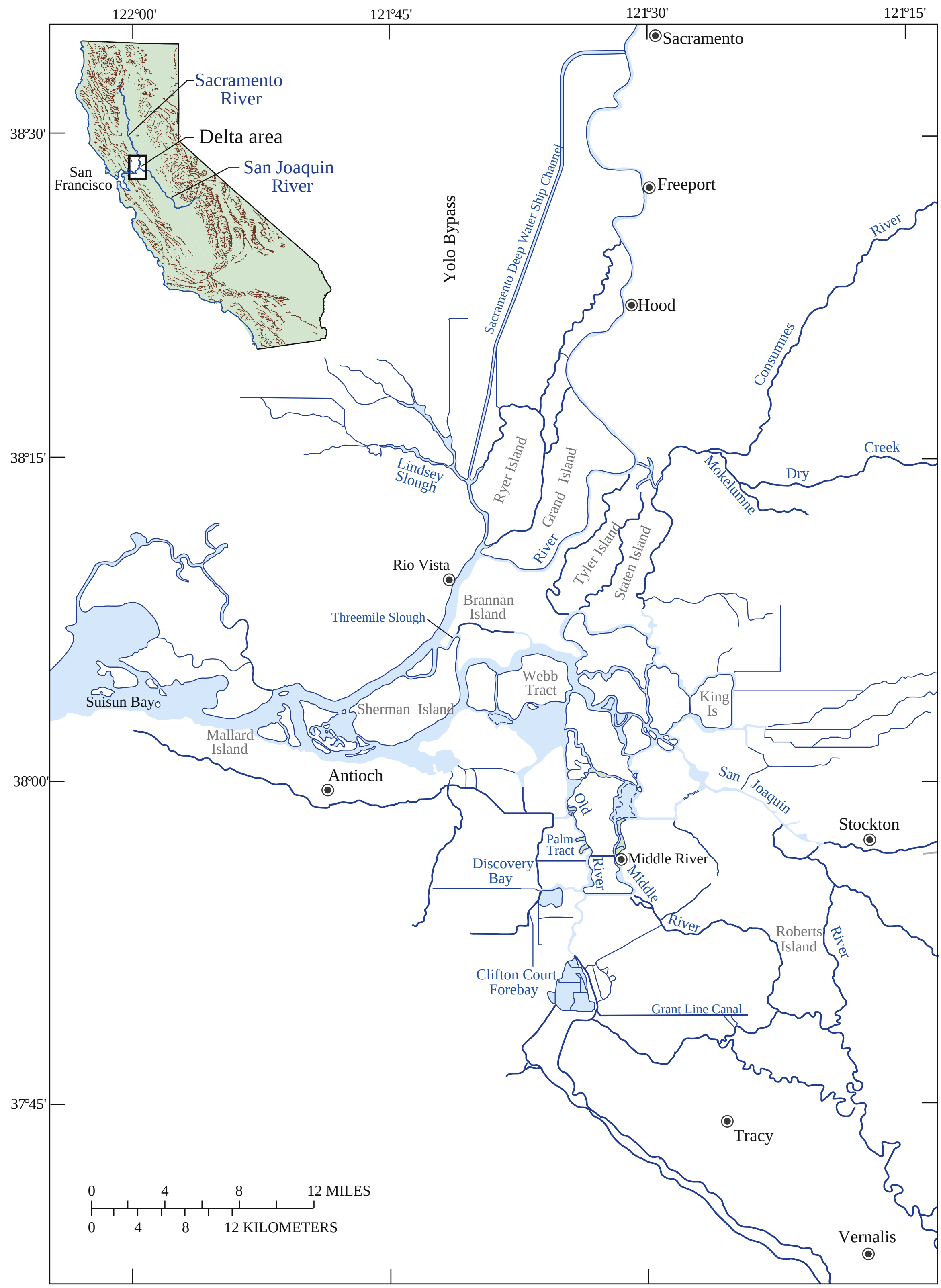

Fig. 2. The Sacramento–San Joaquin Delta.

related to inundation from rising sea-levels at that time (Drexler et al., 2009). After rapid sea level rise in the Early Holocene of up to 2 m per century (Atwater et al., 1977), Central Bay and San Pablo Bay had filled their current basins by ~5 ka (Atwater, 1979), with evidence suggesting the initial development of fringing tidal salt marshes at ~4.7 ka (Goman et al., 2008). McGann (2008) recognized numerous climate oscillations between warm/dry and cool/wet conditions over the last 3.9 ka, based on the faunal assemblages and an isotope record of a core from South Bay that are shaped by variations in fluvial discharge and water temperature. The top of the core is dominated by the invasive

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foraminifera *Trochammina hadai*, an indicator of pollution and eutrophication of the modern estuary, that is thought to have arrived in San Francisco Bay in the early 1980s (McGann et al., 2000).

2.2. Modifications to the natural system

2.2.1. Hydraulic mining

Major anthropogenic changes to the Bay (Fig. 3) began during the period of large-scale hydraulic gold-mining in the Sierra Nevada from 1852 to 1884 (Gilbert, 1917; Krone, 1979) and have continued to the present. Over 850 million m^3 of sediment was discharged into watersheds that drain into San Francisco Bay due to hydraulic mining (Gilbert, 1917), with a net sediment deposition of over 350 million m^3 in the Bay between 1856 and 1887 (Capiella et al., 1999; Foxgrover et al., 2004; Jaffe et al., 2007; Fregoso et al., 2008). This period of high sedimentation also coincided with abnormally high regional precipitation conditions: stations in Southern California established annual and monthly precipitation records in the 1880s, and the 3 largest floods in the historical record occurred between 1861 and 1891 (i.e., January 1862, December 1867, and February 1891). The first flood had well-documented massive, state-wide impacts (Engstrom, 1996), and the latter two were associated with El Niños (Sidler, 1968; Quinn et al., 1987). These resulting anomalous discharge conditions aided the movement of sediment into San Francisco Bay during this time period. Due to this enormous sediment influx, there was a dramatic seaward migration of the Bay shoreline, including the development of extensive intertidal flats and tidal marshes (Gilbert, 1917; Peterson et al., 1993; Jaffe et al., 2007). Bouse et al. (2010) quantitatively linked the sediment produced by hydraulic mining with the massive influx of sediment in San Francisco Bay using radionuclide dating, bathymetric reconstruction, and geochemical tracers, including mercury. In addition, surface sediment cores extracted in 1990 were still found to contain up to 43% hydraulic mining debris, indicating an ongoing remobilization and redistribution of this sediment within the system, with mercury contamination still posing a concern (David et al., 2009). Gilbert (1917) estimated that the effects of the mining would continue until ~1960s, and it has been demonstrated that the main pulse of bed sediment passed Sacramento by 1950 (Meade, 1982), aided by the construction of dams throughout the watershed (Wright and Schoellhamer, 2004).

2.2.2. Delta and other watershed modifications

Construction of dams, reservoirs, flood-control bypasses, and bank protection in the 20th century trapped and/or reduced the transport of sediment to the Bay (e.g., Brice, 1977; Wright and Schoellhamer, 2004; Whipple et al., 2012). Three of the largest dams in the Sacramento River watershed (Oroville, Folsom, and Englebright), which were constructed between 1940 and 1967, had impounded 85 Mm^3 of sediment by the end of the 20th century (~96 Mt, assuming a specific dry weight of the sediment deposit of 1121 kg/m^3; Vanoni, 1975) (U.S. Bureau of Reclamation, 1992; California Department of Water Resources, 2001; Childs et al., 2003). Not only do dams and reservoirs trap sediment, they also regulate down channel flows, often reducing or eliminating the peak flows that transport the majority of the sediment. However, there is no evidence of this in the Delta (Wright and Schoellhamer, 2004) where the frequency of high flows has been increasing (Schoellhamer, 2011). Canuel et al. (2009) determined that sediment accumulation rates in the Delta were 4–8 times greater prior to 1972 than after, and Jassby et al. (2002) noted a decrease in suspended-solid concentrations in the Delta from 1975 to 1995.

On the other hand, the extensive levee system in the Central Valley and Delta has served to isolate the flood plain from the main river

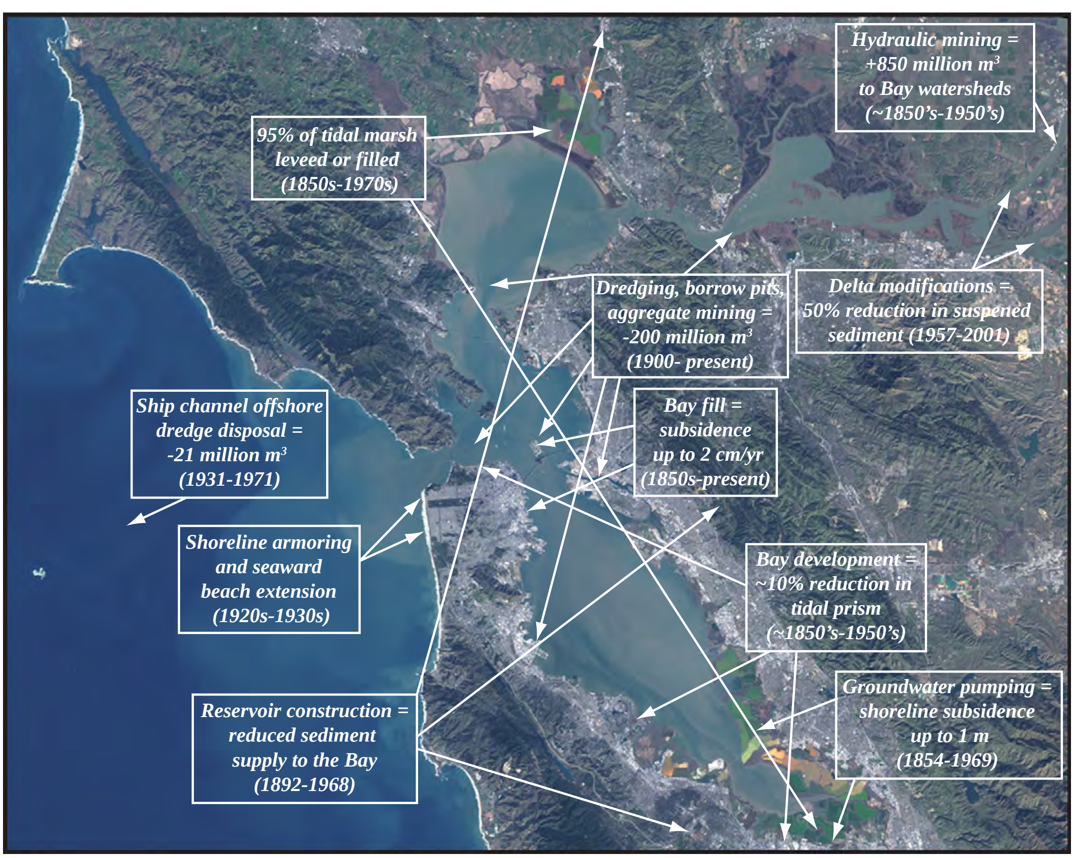

Fig. 3. Examples of major anthropogenic activities and approximate time period of influence to the San Francisco Bay Coastal System. See text for appropriate references.

channels, potentially increasing the sediment yield, along with logging, urbanization, agriculture, and grazing (Wright and Schoellhamer, 2004; Whipple et al., 2012). Construction activities and other forms of urbanization can generate sediment yields that are two orders of magnitude higher than erosion rates reported for stable urbanized areas, and even higher when compared to primarily natural areas with low or no measurable human impact (Lewicki and McKee, 2010). Suspended sediment yield from Guadalupe River, a small tributary watershed draining to the South Bay, was 4–8 times higher in the mid-20th century, during urbanization, than the early 21st century (McKee et al., 2004; Schoellhamer et al., 2008b), and yields from the Alameda Creek watershed also draining to the South Bay, Colma Creek, south San Francisco, and Cull Creek in the East Bay hills also appear to have decreased since the 1960s (Philip Williams and Associates and San Francisco Estuary Institute, 2006). However, overall it is not clear what the trends have been over the longer history of intensive local watershed development in the 9-county Bay Area since the 1850s.

2.2.3. Subsidence

Extensive groundwater pumping in the Santa Clara Valley, particularly from 1916 to 1966, led to as much as 4 m of local subsidence in San Jose, including up to 1 m of subsidence along the southern reaches of the South Bay shoreline, leading to the extensive flooding of low-relief land adjacent to the Bay (Poland and Ireland, 1988). In response, vegetation in South Bay shifted from high marsh vegetation to cordgrass but widespread marsh degradation did not occur because of rapid surface sediment accumulation (Patrick and DeLaune, 1990; Watson, 2004). Some of the submerged land has been recovered over the last several decades due to more responsible groundwater pumping practices (Galloway et al., 1999; Schmidt and Bürgmann, 2003). More recently, the largest vertical rates of change measured in the San Francisco Bay area are actually due to non-tectonic processes, particularly the consolidation of Bay mud and artificial fill that comprise a large proportion of the area's shoreline. For example, the northwestern tip of Treasure Island dropped ~2 cm/year from 1992 to 2000 (Ferretti et al., 2004), and subsidence up to 1 cm/year occurs along natural, mud-dominated shoreline areas (Bürgmann et al., 2006).

2.2.4. Direct sediment removal and Bay modifications

Over the last century, a minimum of 200 million m^3 of sediment has been permanently removed from the San Francisco Bay Coastal System through dredging, aggregate mining, and borrow pit mining, including at least 54 million m^3 of sand-sized or coarser sediment from Central Bay (U.S. Army Corps of Engineers, 1996; Friends of the Estuary, 1997; Chin et al., 2004; Dallas, 2009; Dallas and Barnard, 2009, 2011). From the mid-19th to late 20th century, the tidally-affected surface area was reduced by ~two-thirds due to ~95% of the tidal marsh in San Francisco Bay and the Delta being leveed or filled (Atwater et al., 1979).

Aggregate mining has been active in San Francisco Bay starting in the late 1800s, particularly on Point Knox and Presidio Shoals in Central Bay, with removal regulated since 1952. Aggregate mining currently removes approximately 0.9 million m^3/year of sediment in Central Bay and Suisun Bay (Hanson et al., 2004). Dredging removes about 3 million m^3/year of sediment out of navigation channels and from other channel and berth maintenance projects, with the majority of this material permanently removed from the San Francisco Bay Coastal System via deep-water disposal in the Pacific Ocean (Dredged Material Management Office, 2008; Keller, 2009; San Francisco Estuary Institute, 2009), roughly equivalent to the annual sediment supply from the Central Valley (Schoellhamer et al., 2005).

In Central Bay, human impacts include active sand mining, dredging and disposal, artificial shoreline fill, borrow pit mining, and underwater rock pinnacle blasting (Chin et al., 1997, 2004, 2010; Dallas, 2009; Dallas and Barnard, 2009, 2011; Barnard and Kvitek, 2010). From 1855 to 1979, 92% of tidal marsh and 69% of intertidal mud flats were eliminated from Central Bay by human development, resulting in total area loss of 4%. Bathymetric change at a borrow pit created near Bay Farm Island from 1947 to 1979 indicates the removal of 25 Mm^3 of sediment (Fregoso et al., 2008). Navigational dredging of Oakland Harbor began in 1874 and eventually at ~17 sites in Central Bay: a total of ~70 Mm^3 of sediment was removed from 1931 to 1976 (U.S. Army Corps of Engineers, 1975). Some of this material was used on land, some disposed of nearby, such as just offshore of Alcatraz Island and Yerba Buena Island that occasionally created dangerous shoals, and some at deep-water disposal sites. Borrow pits in Central Bay were utilized for numerous major developments, including the 22.5 Mm^3 dredged to create Treasure Island in 1935 (Scheffauer, 1954).

2.3. Changes to the historical sediment supply

Prior to the Gold Rush in 1849, Gilbert (1917) estimated that the sediment supply from the Delta to the Bay was ~1.5 Mm^3/year (or 1.3 Mt/year assuming a bulk density of 850 kg/m^3 per Porterfield, 1980). Based on bathymetric change data, Gilbert (1917) calculated a total sediment load of 876 Mm^3 between 1849 and 1914 (13.5 Mm^3/year, 11.5 Mt/year, 9 times the pre-Gold Rush rate), with 38 Mm^3 passed through to the Pacific Ocean. The sediment supply peaked near 1884 at $>$ 24.9 Mt/year (Ganju et al., 2008).

Historically, the majority of the sediment load to San Francisco Bay was supplied from the Delta (Krone, 1979; Porterfield, 1980), with the Sacramento River producing seven times the sediment yield of the San Joaquin River (Oltmann et al., 1999). Porterfield (1980) used rating curves from individual Bay tributaries to estimate a total load of 6.6 Mm^3/year (5.6 Mt/year) from 1909 to 1966, 86% of this coming from the Delta. From 1957 to 1966 the load from the Delta was slightly less at ~83%. Porterfield (1980) sampled the Sacramento River bed numerous times in the 1960's during a range of flow conditions, and found the median grain size (D_{50}) to consistently range between 0.29 and 0.39 mm. From 1957 to 1966, bedload was estimated to account for 1.4% of the total sediment discharge, but sand discharge accounted for 52% of the total load. The San Joaquin River carried much less sand during this period, only 28% of the total load. Porterfield (1980) also used Gilbert's (1917) projections to estimate a total flux to the ocean of only 0.3 Mm^3/year from 1909 to 1966, 5% of the estimated supply that entered the Bay annually. Suspended sediment loads decreased by 50% from the Sacramento River from 1957 to 2001, from ~2-3 Mt to 1–2 Mt, or a total reduction of ~25 Mt (Wright and Schoellhamer, 2004; Singer et al., 2008). Schoellhamer et al. (2005) estimated that by the end of the 20th century, sediment supply to the Bay from the Delta and local tributaries was roughly equal, a trend that had been predicted by Krone (1979) and most recently confirmed by Lewicki and McKee (2010).

Ganju et al. (2008) used these prior studies as a guide to reconstruct decadal sediment loads for the Sacramento–San Joaquin Delta from 1851 to 1958, with measured data since 1958 (Ogden Beeman and Associates, 1992; USGS, http://waterdata.usgs.gov/nwis) used to complete the historical sediment load time-series (Fig. 4). Ganju et al. (2008) estimated a decrease in mean annual sediment loads to the Delta from a high of greater than 10 Mt/year in the late 19th century to less than 3 Mt/year in the latter half of the 20th century, with a dramatic decrease after 1910. The timing of dramatic changes in sediment loads is tied to the onset and subsequent cessation of hydraulic mining, followed by major Delta modifications, including the construction of reservoirs, in-stream diversions in the Sacramento and San Joaquin Valleys, and in-Delta withdrawals (e.g., freshwater pumping) (Knowles and Cayan, 2004).

2.4. Geomorphic response of the San Francisco Bay Coastal System

The precise impact of the aforementioned disturbances and changes to the sediment supply for the San Francisco Bay Coastal System is

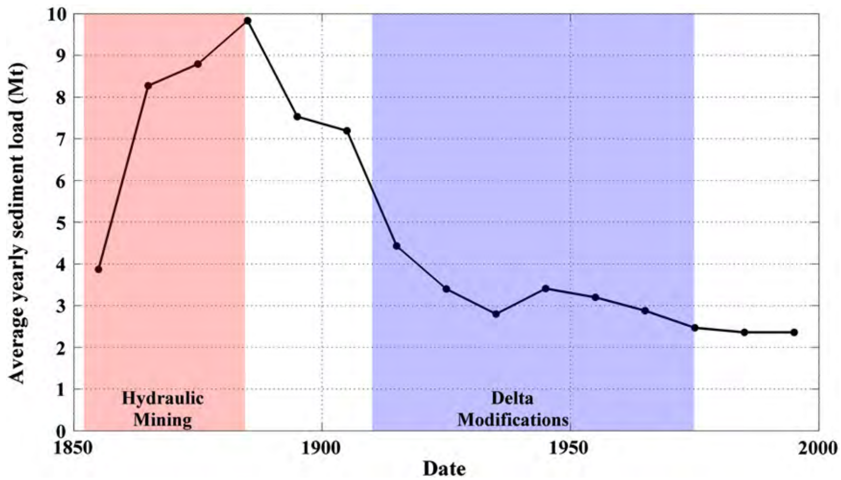

Fig. 4. Reconstructed decadal sediment load from the Sacramento and San Joaquin rivers (from Ganju et al., 2008, using bulk density estimates of 529 kg/m^3 per Schultz, 1965; Krone, 1979), with the major periods of hydraulic mining (1852–1884) and Delta modifications (1910–1975) highlighted.

difficult to quantify, although a series of bathymetric change studies have been effective in developing potential causal links. Net sediment volume changes to the Bay from 1855 to 1989 were derived from measured historic bathymetries by Capiella et al. (1999), Foxgrover et al. (2004), Jaffe et al. (2007), and Fregoso et al. (2008). These studies, coupled together, are summarized as follows: +350 Mm^3 (1855–1887) attributed to hydraulic mining; +10 Mm^3 (1887–1922) attributed to flushing out of hydraulic mining sediment into the Pacific Ocean; +120 Mm^3 (1922–1947) attributed to additional influxes of stored hydraulic mining sediment, and urbanization and increased agricultural land use in the watersheds; −180 Mm^3 (1947–1989) attributed to sediment trapping/diversion in the Delta, waning of the hydraulic mining and urbanization pulses, and direct removal of sediment from the Bay for dredging, aggregate mining, and borrow pits (Barnard and Kvitek, 2010; Dallas and Barnard, 2011; Schoellhamer, 2011).

After an estimated net of 115 Mm^3 of sediment was deposited in Suisun Bay from 1867 to 1887, the sub-embayment quickly began to erode, with a total net loss of ~262 Mm^3 from 1887 to 1990 (Capiella et al., 1999), largely attributed to the cessation of hydraulic mining and river management projects (Wright and Schoellhamer, 2004). San Pablo Bay only became net erosional in the mid-20th century (Jaffe et al., 2007).

Fregoso et al. (2008) demonstrated that Central Bay gained 42 Mm^3 of sediment from 1855 to 1979, but there were periods of erosion (−2 Mm^3/year, 1855–1895) and accretion (+3 Mm^3/year, 1895–1947). Most notably, the last time period was net erosional (−2 Mm^3/year, 1947–1979), particularly in West-central Bay (−31 Mm^3), coinciding temporally and spatially with the onset of large-scale aggregate mining.

Focusing on the last half-century for the entire San Francisco Bay Coastal System, sediment loss trends have been documented in North Bay (i.e., San Pablo (Jaffe et al., 2007) and Suisun Bay (Capiella et al., 1999)), Central Bay (Fregoso et al., 2008; Barnard and Kvitek, 2010), and the San Francisco Bar (i.e., mouth of San Francisco Bay: Hanes and Barnard, 2007; Dallas and Barnard, 2009, 2011), with only South Bay showing net accretion (Jaffe and Foxgrover, 2006) (Fig. 5). The mouth of San Francisco Bay lost over 90 million m^3 of sediment between 1956 and 2005 (Hanes and Barnard, 2007), Central Bay lost 52 million m^3 of sediment between 1947 and 1979 (Fregoso et al., 2008), and an additional 14 million m^3 of sediment between 1997 and 2008, linked directly to aggregate mining (Barnard and Kvitek, 2010). Applying rates of volume change for each sub-embayment and the San Francisco Bar from 1956 to 2005 would result in an estimated sediment loss of 240 million m^3 from the entire San Francisco Bay Coastal System. In 1999 there was a 36% step decrease in suspended sediment concentrations observed inside the Bay between the 1991–98 and the 1999–2007 water years, broadly attributed to the depletion of the 'erodible sediment pool' created by hydraulic mining and possibly urbanization, and further reduced by river bank protection, and sediment trapping behind dams and in flood bypasses (Schoellhamer, 2011).

For the open coast, there has been a net reduction of the surface area and volume of the ebb-tidal delta since the late 19th century, which has been linked to the decreasing sediment supply from San Francisco Bay and shrinking of the tidal prism (Gilbert, 1917; Conomos, 1979; Battalio and Trivedi, 1996; Hanes and Barnard, 2007; Dallas, 2009; Dallas and Barnard, 2009, 2011). As further evidence of the reduced sediment supply, the historical rates (late 1800s to 1998) of shoreline erosion south of San Francisco are the highest in California (Hapke et al., 2006, 2009) and have accelerated by 50% between Ocean Beach and Pt. San Pedro (Fig. 1) since the 1980s (Dallas and Barnard, 2011). Along with a reduced sediment supply, grain size, and tidal prism that have been linked to persistent regional erosion (Barnard et al., 2012b), scour associated with an exposed sewage outfall pipe that was constructed in the late 1970s offshore of Ocean Beach has locally exacerbated coastal erosion (Hansen et al., 2011).

The geomorphic and sedimentary changes caused by the hydraulic mining sediment pulse and its subsequent diminishment have affected the estuarine ecosystem. Hydraulic mining sediment contributed to the creation of 75 km^2 of tidal marsh habitat (Atwater et al., 1979). Mercury that was part of the mining debris continues to act as a legacy pollutant in the Bay and is found in elevated levels in Bay biota (Ely and Owens Viani, 2010). Suspended sediment in San Francisco Bay limits light availability, photosynthesis, and phytoplankton growth (Cloern, 1987). Decreased suspended-sediment concentration (SSC) after 1999 has contributed to increased chlorophyll concentrations, larger spring phytoplankton blooms, and reoccurrence of autumn blooms (Cloern et al., 2007; Cloern and Jassby, 2012). Reduced SSC may be one of several factors contributing to a collapse of several San Francisco Bay estuary fish species that occurred around 2000 (Sommer et al., 2007).

3. Present-day sediment transport and associated physical processes

3.1. The watershed

On average, San Francisco Bay receives >90% of its freshwater influx from the Sacramento–San Joaquin Delta (Conomos, 1979), with the remainder coming from >450 smaller drainages surrounding the Bay (McKee et al., this issue). The majority of sediment is

Fig. 5. Measured bathymetric changes over the last ~50 years in the San Francisco Bay Coastal System. See text for appropriate references.

delivered to the Bay in the highest flows during the wet season, from late fall-early spring (McKee et al., 2003, 2006; David et al., 2009), for which 87–99% of total load is suspended (Porterfield, 1980; Wright and Schoellhamer, 2004; Schoellhamer et al., 2005).

3.1.1. The Delta

The Sacramento–San Joaquin River Delta is a complex network of natural and man-made channels at the confluence of the two rivers (Fig. 2). The Delta is the outlet for 40% of California's drainage area and 92% of the San Francisco Bay drainage area (Porterfield, 1980). The annual mean freshwater discharge rate from the Delta into the Bay is 800 m^3/s and the record Delta outflow is 17,800 m^3/s in February 1986 (California Department of Water Resources, 2007). Levee construction and draining of marshlands began in the latter half of the 1800s (Atwater et al., 1979). As a result, the Delta today consists of a network of slough channels surrounding former marshlands commonly termed 'islands' which are primarily used for agriculture. Because of the high organic content of Delta soils, draining of marshes has resulted in significant land subsidence such that most of the islands are currently below mean sea level, some by as much as 4 m. The Delta also contains the pumping facilities that divert freshwater to the San Joaquin Valley and Southern California. The channels are tidal and freshwater flows are managed to prevent salinity from intruding landward of the western Delta. Wright and Schoellhamer (2005) used continuous measurements of suspended-sediment flux to develop a sediment budget for the Delta for water years 1999–2002. During that time period, 85% of the sediment that entered the Delta came from the Sacramento River, 13% came from the San Joaquin River, and the eastside tributaries (Cosumnes and Mokelumne rivers) supplied the remaining 2%. Riverine sediment delivery to the Delta was episodic with 82% of the sediment being delivered during the wet season (31% of the time). The lower Sacramento River is the primary sediment transport pathway because at least 82% of the sediment entering the Delta from the Sacramento River watershed either deposited along the Sacramento River or moved past Mallard Island and into San Francisco Bay. Of the sediment that entered the Delta, 67 ± 17% deposited there and the remainder entered the Bay. Schoellhamer et al. (2012) present a conceptual model of sedimentation in the Delta.

3.1.2. Recent sediment supply and delivery patterns

Recent estimates of suspended loads entering the estuary from the Sacramento–San Joaquin Delta range from 1 to 1.2 Mt/year (McKee et al., 2006; David et al., 2009) to 4 Mt/year (Shvidchenko et al., 2004), with most of this likely mud-sized. As suspended sediment loads from the Delta have diminished, the relative importance of loads from the small local tributaries has increased. Lewicki and McKee (2010) estimated that suspended sediment loads entering the Bay from local watersheds can vary by a factor of 2–4 interannually, with a mean rate of 1.3 Mt/year (35% associated with urbanized watersheds), significantly higher than the 0.3–1.0 Mt/year estimated in prior studies, summarized in McKee et al. (2003). These local watersheds may now account for ~56% of the total suspended load entering San Francisco Bay: the precise accounting has implications for the degradation of riparian habitats via siltation, the transport of particle-associated pollutants, dredging volumes, and accretion rates of tidal wetlands (David et al., 2009; Lewicki and McKee, 2010). These local watersheds typically produce 50% of their annual discharge and 90% of the sediment load (80% of which is mud; David et al., 2009; Lewicki and McKee, 2010) during only a few days (Kroll, 1975). More recent research by McKee et al. (2006) reinforces that episodic sediment loads dominate the sediment supply to the Bay, where 10% of annual load can be delivered in one day, and over 40% within seven days during an extremely wet year. Within this special issue, the latest observations of sediment supply volumes and trends will be presented

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(e.g., McKee et al., this issue), with particular focus on the resulting sediment transport processes and geomorphic evolution of the San Francisco Bay Coastal System (e.g., Hansen et al., this issue; Schoellhamer et al., this issue).

The vast majority of sediment from minor drainages (~>90%) is supplied as suspended load (McKee, 2006). Greater than 90% of suspended sediment in both Coyote Creek and Guadalupe River (larger South Bay tributaries) is silt- and clay-sized materials and 88% of suspended sediment is <0.02 mm in the Guadalupe River. Zone 6 Line B (another South Bay tributary) differs due to its small watershed size and steep stream slope; only 77% of suspended sediment transported is finer than 0.0625 mm. These data suggest that most of the suspended sediment loads are likely to pass through dredged channels and onto the Bay margin where they might be available for wetland maintenance or restoration (McKee, 2006). During average flows, sand is typically only a few % of the total load, but can be as high as 70% during high flows, and may account for 50% of the annual load during a very wet year, the remainder being mud (Porterfield, 1980). Sand and gravels are likely to be caught in flood control channels and removed by maintenance dredging of the larger and managed tributary systems (Collins, 2006; McKee, 2006); further research is needed to inventory these processes for individual channels and the Bay as a whole.

3.2. San Francisco Bay

San Francisco Bay consists of four sub-embayments, covering an area of 1200 km^2 (below MSL). In addition to the Bay, the San Francisco Bay Coastal System also includes the open coast littoral cell, extending from Pt. Reyes to Pt. San Pedro, the ebb-tidal delta (i.e., San Francisco Bar) at the mouth of San Francisco Bay, the inlet throat (i.e., Golden Gate), and the Sacramento–San Joaquin Delta mouth (Fig. 1). Morphologically, the mouth of San Francisco Bay is dominated by the San Francisco Bar, a massive sub-sea surface ebb-tidal delta that covers a region of approximately 175 km^2, with an average depth of 17 m. Sediments are derived from watersheds of the Sacramento–San Joaquin Delta (i.e., Sierran, notably granitic) and local tributaries (Gilbert, 1917; Yancey and Lee, 1972; Schlocker, 1974; Porterfield, 1980; McKee et al., 2003, 2006; Keller, 2009; Lewicki and McKee, 2010), and the local coast range that outcrops along the open coast in the Golden Gate and Central Bay (i.e., Franciscan Complex, notably chert and serpentine, and younger volcanic and sedimentary rocks). The modern Bay floor and adjacent open coast seafloor are primarily comprised of sand and mud, overlying metamorphic and sedimentary bedrock: the shallowest depths to bedrock and intermittent bedrock exposures are most common in Central Bay (Trask, 1956; Goldman, 1969; Carlson and McCulloch, 1970; Chin et al., 2004), within the Golden Gate (Barnard et al., 2006a,b), the northern open coast, and Carquinez Strait (Jachens et al., 2002). The bottom sediments are mud-dominated in South Bay and in the shallower (<4 m), lower tidal energy areas of Central Bay, San Pablo Bay, and Suisun Bay. Sand is prevalent in the open-coast littoral system, Golden Gate and San Francisco Bar, and the deeper portions of Central Bay, San Pablo Bay, and Suisun Bay, particularly within the main tidal channels (Conomos and Peterson, 1977) where large bedforms (~10–100 m wavelengths) are common (e.g., Rubin and McCulloch, 1979; Chin et al., 2004; Barnard et al., 2012a).

Tides at the Golden Gate (NOAA/Co-ops station 9414290) are mixed, semi-diurnal, with a maximum tidal range of 1.78 m (MLLW–MHHW, 1983–2001 Tidal Epoch). Minor tidal fluctuations extend up to Sacramento, 155 km from the Golden Gate. The tidal prism exceeds the volume of freshwater inflow by one to two orders of magnitude. Freshwater input represents less than 1% (~19% during record flow) of the spring tidal prism of 2×10^9 m^3 served by the Golden Gate tidal inlet (Barnard et al., 2007a). Tidal currents are therefore far stronger than freshwater flows except during extreme flow conditions upstream, and cause most of the mixing in the estuary (Cheng and Smith, 1998). Even during the highest river discharge events, water levels at the Golden Gate are only increased by a few centimeters, although freshwater surface flows may be significant (Kimmerer, 2004).

Though less dominant than tidal forcing, gravitational circulation can develop, particularly during strong stratification (e.g., Monismith et al., 1996) and neap tidal conditions. Gravitational circulation has been observed at deep locations in the estuary, such as the Golden Gate (e.g., Conomos, 1979) and Carquinez Strait (Smith et al., 1995). Schoellhamer (2001) demonstrated that estuarine turbidity maxima form when salinity and gravitational circulation are present but they are not associated with a singular salinity. Bottom topography enhances salinity stratification, gravitational circulation and estuarine turbidity maxima formation seaward of sills. The spring/neap tidal cycle also affects locations of estuarine turbidity maxima. Salinity stratification in Carquinez Strait, which is seaward of a sill, is greatest during neap tides, causing the tidally-averaged suspended-sediment concentration in Carquinez Strait to be less than that landward at Mallard Island in eastern Suisun Bay. Spring tides cause the greatest vertical mixing and suspended-sediment concentration in Carquinez Strait. Therefore, surface estuarine turbidity maxima always are located in or near the Strait during spring tides, regardless of salinity. During neap tides, surface estuarine turbidity maxima are landward of Carquinez Strait and in the salinity range of 0–2‰.

Wave energy throughout the Bay is mainly generated by local winds, while ocean swell penetrating through the Golden Gate can only significantly affect exposed portions of Central Bay, such as the north-facing San Francisco city shoreline (Hanes et al., 2011b) and the mudflats in eastern Central Bay (Talke and Stacey, 2003). Waves play a minor role in sediment transport throughout the deeper portions of the Bay. However, the impact of local, wind-generated waves and ocean swell can induce significant turbulence and sediment transport in shallow, fetch-exposed mudflats (Schoellhamer, 1996; Warner et al., 1996; Talke and Stacey, 2003).

The U.S. Geological Survey began measuring suspended sediment concentrations (SSCs) at several locations every 15 min in San Francisco Bay in 1991, an effort that continues to this day at seven locations (Schoellhamer, 2011; Buchanan and Morgan, 2012). Approximately 89% of the SSC variability in the Bay is associated with tidal cycles (i.e., semidiurnal, fortnightly, monthly, semi-annual), seasonal wind, and river supply (Schoellhamer, 2002). SSC is lowest during the summer and into the fall, as the supply of erodible sediment decreases (Schoellhamer, 2002), and overall, concentrations are highest in lower South Bay, moderate in Suisun and San Pablo Bays, and lowest in Central Bay (Schoellhamer, 2011).

3.2.1. Suisun Bay

The majority of Suisun Bay is shallower than 5 m and mud-dominated, with several deeper (10–15 m) sandy, bedform-covered channels running east–west through the sub-embayment that splits from the main Delta channel. Suspended sediment transport peaks during winter freshwater flows from the Delta into Suisun Bay, with a portion of the material passing through to San Pablo Bay. During the spring and summer, persistent onshore winds generate short-period waves, resuspending sediment in both Suisun and San Pablo Bays: landward near-bed flows and a gradient of suspended sediment concentration combine to transport sediment up estuary from San Pablo to Suisun Bay, but by the fall the finer fraction of the erodible sediment pool is significantly reduced (Krone, 1979; Ruhl and Schoellhamer, 2004; Ganju and Schoellhamer, 2006). Tidal currents in the channels approach 1 m/s and estuarine turbidity reaches a maximum along the north side of Carquinez Strait, due to high flow velocities (Schoellhamer and Burau, 1998). Moskalski and Torres (2012) found that wind, river discharge, and tides explained up to 75% of the variance of subtidal SSC. Ganju et al. (2009) established that tidal and wind-wave forcing, along with total load and peak flow magnitude, are the most important parameters for simulating geomorphic change. Carquinez Strait, which connects San Pablo Bay with Suisun Bay, reaches a depth of 35 m, and is flanked by rock (Kimmerer, 2004).

3.2.2. San Pablo Bay

San Pablo Bay contains a single main channel, 11–24 m deep with a mostly sandy bed, which connects Carquinez Strait with Central Bay (Jaffe et al., 2007). Extensive shallow areas (most <4 m deep) and tidal flats are mud-dominated and cover 80% of San Pablo Bay (Locke, 1971). In effectively modeling multi-decadal deposition patterns in San Pablo Bay, van der Wegen et al. (2011) found that river discharge and sediment concentration had a strong positive influence on sedimentation. The inclusion of waves in the model was found to decrease deposition rates, and along with tidal currents, had the most significant impact on sediment distribution. Waves are local, wind-driven with limited fetch, and have been measured as high as 0.6 m (Schoellhamer et al., 2008a). When tidally-driven mixing processes are weak, in particular during neap tides, stratification and gravitational circulation are common. Stacey et al. (2008) note that tidally-periodic stratification can also generate gravitational circulation, while Ganju et al. (2006) demonstrated that low river flow effectively reduced stratification in Carquinez Strait. Salt can intrude from the Pacific Ocean into Suisun Bay during the dry months but only reaches into San Pablo Bay during the wet months (Monismith et al., 2002), when water levels are elevated by ~20 cm and sediment transport is an order of magnitude higher. During high flows into Suisun Bay from the Delta, the sediment pulse takes multiple days to reach San Pablo Bay (van der Wegen et al., 2011).

3.2.3. South Bay

In South Bay, which receives considerably less river flow than the other sub-embayments (Kimmerer, 2004), spring tidal currents typically exceed 1 m/s in the channel and 0.4 m/s on the shoals (Schoellhamer, 1996). The South Bay floor is dominated by mud-sized sediments primarily derived from local watersheds, based on the heavy mineral assemblage featuring jadeite and glaucophane that is common in the bordering Coast Range to the southeast (Yancey and Lee, 1972), although contributions from the San Joaquin–Sacramento River watershed are also likely. Strong winds are typical during winter storms and summer sea breezes (~7 m/s), resulting in significant wave generation, sediment resuspension and basin wide circulation (Conomos et al., 1985), possibly directed landward in the shallower eastern channel and seaward in the main channel (Walters et al., 1985). Bottom currents are seasonally-reversing and slower than the other reaches, while surface non-tidal currents are primarily generated by prevailing summer and winter storm winds and winter freshwater flows from the Delta (Conomos, 1979). Sediment concentrations in South Bay are generally higher during flood tides as wind waves resuspend sediment during low water levels, particularly during the persistent westerly and northwesterly winds in the summer and fall, resulting in a net sediment flux toward the southeast (Lacy et al., 1996). While wind waves are important for cohesive sediment resuspension on shoals, large increases in sediment flux are due to the nonlinear interaction of both wind waves and tidal currents (Brand et al., 2010). In the channels, sediment concentration peaks during the lowest spring tides, when turbid water is advected from the shoals (Schoellhamer, 1996).

3.2.4. Central Bay

Landward of the Golden Gate, Central Bay is the deepest part of the Bay, contains the coarsest sediment, and the strongest currents (Chin et al., 1997, 2004). The western section is dominated by sandy bedform fields (up to 90-m wavelengths) and exposed bedrock, while the eastern Bay floor adjacent margins are primarily mud-dominated and featureless (Rubin and McCulloch, 1979; Barnard and Kvitek, 2010; Chin et al., 2010; Barnard et al., 2011b, 2012a). Sediment is up to 100 m thick (Carlson and McCulloch, 1970; Chin et al., 2004). Bedrock pinnacles and sandy shoals focus currents and produce a wide range of bedform morphologies that were first mapped in the late 1970's using side-scan sonar (Rubin and McCulloch, 1979) and several decades later in high resolution multibeam (Chin et al., 1997; Dartnell and Gardner, 1999; Barnard et al., 2011b, 2012a). Based on surficial grain size distributions and the multibeam, backscatter and sidescan data of Greene and Bizarro (2003), Chin et al. (2010) suggested that the sand in Central Bay is derived from either outside the Bay, shoreline sediments and outcrops in the vicinity of the Golden Gate (the coarser sands), or from San Pablo Bay (finer sands), with little mixing of the two fractions.

3.3. Golden Gate

Through the Golden Gate, the channel floor is bedrock with a maximum depth of 113 m, where tidal currents accelerate through the erosion-resistant rocky strait. The approximate depth and formation have been linked to either downcutting of the Sacramento River during the Last Glacial Maximum (Louderback, 1951) or a major fault (Schlocker, 1974), with ongoing minor incision due to tidal scour. As these currents decelerate, large bedforms are created on either side of the Golden Gate Bridge/strait, including one of the largest sand wave fields in the world (i.e., both spatial extent and wavelength) just seaward of the strait (Barnard et al., 2006a,b). Tidal currents in the inlet throat peak at over 2.5 m/s, and can exceed 1 m/s even on the edge of the ebb-tidal delta, over 10 km from the Golden Gate (Barnard et al., 2007a). These powerful and spatially variable currents result in an incredibly diverse array of bedform sizes and shapes both landward (Rubin and McCulloch, 1979; Chin et al., 1997) and seaward of the Golden Gate (Barnard et al., 2006a,b, 2012a).

The critical interface between San Francisco Bay and the open ocean (a.k.a., the Golden Gate) is particularly complex, with strong vertical stratification and lateral variability in current velocities and tidal phase (Largier, 1996; Petzrick et al., 1996). Exchange is influenced by a number of factors, including tidal flow, gravitational and lateral circulation (ebb-dominated on the northern side and flood-dominated on the southern side), wind stress, atmospheric pressure gradients, and changes in water levels due to spring–neap cycles (Conomos, 1979; Walters et al., 1985; Walters and Gartner, 1985; Largier, 1996; Petzrick et al., 1996). Residual flow through the Golden Gate is driven by subtidal processes such as tidal pumping, baroclinic flow, tidal trapping of an eddy, and enhanced frictional phasing by a lateral density gradient (Fram, 2005; Martin et al., 2007). While tidal forcing dominates circulation overall, baroclinic and barotropic components of wind-driven upwelling can play a critical role in the spring and summer, forcing denser water along the bottom into the Bay, inducing gravitational circulation (Largier, 1996).

Fram et al. (2007) ran transects parallel to the Golden Gate bridge with a boat-mounted acoustic Doppler current profiler (ADCP) and a suite of towed instruments to measure rms instantaneous discharges of 60,000 m^3/s, mean discharges of 600 m^3/s (net seaward), and a mildly stratified channel, with salinities ranging from 30 to 33‰ (top to bottom) in the summer and 32.0 to 32.4‰ in the fall. They also determined that both density gradients and bathymetry influence ocean-estuary exchange, and that overall tidal exchange (i.e., salinity variability between ebb and flood tides) is far less than prior studies indicated (Parker et al., 1972; Largier, 1996). During the same experiment, Martin et al. (2007) measured chlorophyll fluxes between Central Bay and the Golden Gate, and found that fluxes were dominated by tidal pumping, accounting for 64–93% of the net dispersive flux, and the direction of the net advective flux (i.e., the physical mechanism driving flow) was always seaward. Cheng et al. (1993) modeled neap and spring tidal discharge during low Delta flows (~200 m^3/s) at the Golden Gate of 42,000–95,000 m^3/s, and 5000–13,000 m^3/s in Carquinez Strait.

The only direct estimates of suspended sediment transport using in situ measurements across the Golden Gate were performed by

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Teeter et al. (1996). During a two week neap–spring period of low Delta flow conditions, they performed repeated inlet cross-sectional transects using boat-mounted ADCP systems, observing a clear net seaward transport of suspended sediment of 188,000 metric tonnes, with fluxes during ebb flows 44% higher on average than during flood flows. No studies have made direct measurements of bedload transport across the Golden Gate, however, an extensive study of bedform asymmetry covering West-central Bay and the mouth of San Francisco Bay suggests a net seaward flux of bedload through the Golden Gate, further confirmed by applying a hydrodynamically-validated numerical model to estimate the net flux of suspended load and bedload across the inlet throat (Barnard et al., 2012a). The latest research on the net direction and volume of sediment flux across the Golden Gate will be presented in this special issue (Barnard et al., this issue-a,b; Elias and Hansen, this issue; Erikson et al., this issue), essential information for quantifying the impact of a reduced sediment supply from the Bay to the open coast, with numerous estuary management implications (e.g., determining the appropriate location and volumes for responsible aggregate mining, dredging, and disposal).

3.4. The open coast

The open coast is a high-energy coastal environment comprising primarily sandy beaches and bluffs to the south of the Golden Gate, and rocky cliffs and pocket beaches to the north. The geology is controlled by active tectonics with the San Andreas Fault Zone and San Gregorio Fault Zone (Fig. 1) traversing directly through the region (Parsons et al., 2002). This area is susceptible to highly energetic waves, being exposed to swell from almost the entire Pacific Ocean. The average annual maximum offshore significant wave height is 8.0 m, and the annual average offshore significant wave height is 2.5 m (Scripps Institution of Oceanography, 2012). Tidal currents peak at 1.5 m/s immediately adjacent to the Golden Gate entrance along the northern extent of Ocean Beach, and still approach 1 m/s ~5 km north and south of the channel entrance (Barnard et al., 2007a), as is evident by the vast distribution of bedforms throughout the region (Barnard et al., 2012b). The combination of large waves, strong tidal currents, and active tectonics results in an extremely complicated coastal system that has only recently begun to be explored with a comprehensive study led by the U.S. Geological Survey initiated in 2003. This effort has focused on the physical processes controlling the sand waves in the Golden Gate (Barnard et al., 2006a,b; Sterlini et al., 2009; Hanes, 2012), the geomorphic evolution of Ocean Beach and a persistent erosion hot spot (Barnard and Hanes, 2005, 2006; Barnard et al., 2007a,b,c, 2009a,b, 2011a,c, 2012b; Erikson et al., 2007; Eshleman et al., 2007; Hansen and Barnard, 2009, 2010; Hansen et al., 2011, 2013b; Hansen et al., in review; Shi et al., 2011; Yates et al., 2011), and linking the physical processes in the Bay with the open coast (Hanes and Barnard, 2007; Dallas, 2009; Dallas and Barnard, 2009, 2011; Hanes et al., 2011a; Barnard et al., 2012a,b). Beach behavior at Ocean Beach is seasonally-modulated (Hansen and Barnard, 2010), with occasionally severe erosion during winter storms (Barnard et. al., 2011a) carrying large volumes of sediment offshore into an extensive nearshore bar system (Barnard et al., 2011c), while the beach recovers during the lower energy summer and fall (Hansen and Barnard, 2010). However, the morphology of the adjacent ebb-tidal delta affects the distribution of wave heights, which can vary by a factor of two, and sediment transport processes along Ocean Beach, exerting a dominant control on short and long-term beach evolution (Battalio and Trivedi, 1996; Eshleman et al., 2007; Hansen and Barnard, 2009; Jones, 2011; Shi et al., 2011; Hansen et al., 2013b; Hansen et al., in review). South of Ocean Beach, coastal bluff erosion and landsliding are a dominant geomorphic process, driven commonly by over steepening at the toe due to wave action, and/or precipitation-induced groundwater seepage (Collins and Sitar, 2008), sporadically providing significant volumes of sediment to the littoral cell.

3.5. Regional oceanography

Global sea level has been regionally-suppressed along the U.S. West Coast since ~1980 due to the persistence of strong, northwesterly winds (Bromirski et al., 2011). However, northward propagating, coastal-trapped waves can raise sea level along this portion of the California coast up to 30 cm during an El Niño winter (e.g., as occurred during 1982–83 and 1997–98) (Bromirski et al., 2003), with an additional 5–10 cm of decadal variability possibly associated with the Pacific Decadal Oscillation (Mantua et al., 1997). Non-tidal, water level extremes inside San Francisco Bay are dominated by storm surges that propagate from the open ocean into the Golden Gate, through the Bay, and up into the lower reaches of the Sacramento–San Joaquin Delta. Surge can force non-tide fluctuations as high as 70 cm at the Golden Gate, although during extreme events these levels are often exceeded in Suisun Bay due to both surge propagation into the constricted sub-embayment and the commonly coincident timing of high Delta discharge rates due to heavy rainfall (Bromirski and Flick, 2008). Along the exposed outer coast, long period ocean swell dominates the wave energy spectrum throughout the year, although local seas are often generated by strong northwesterly winds in the spring and summer that produce coastal upwelling and generally dominate shelf-scale circulation patterns (Largier et al., 2006; Kaplan et al., 2009) beyond the influence of the Golden Gate, with these persistent winds relaxing during the fall and winter (Largier et al., 1993).

4. Looking to the future-climate change impacts

Rising sea levels over the 21st century (e.g., Vermeer and Rahmstorf, 2009) will increase the frequency of extreme water level events in San Francisco Bay (Cayan et al., 2008), placing additional stress on the San Francisco Bay Coastal System's tidal marshes (including massive restoration projects currently underway), levees, shorelines, and ecosystems. Future warming scenarios for California consistently project more precipitation falling as rain in the Sierras, resulting in higher rainfall-related peaks earlier in the season and weaker snowmelt-related peaks of the Delta hydrographs, as well as higher estuarine salinity (e.g., Knowles and Cayan, 2002, 2004). These changes will undoubtedly impact circulation patterns and shift peak sediment loads to earlier in the year (Ganju and Schoellhamer, 2010).

Knowles (2010) indicated that the present day 100-year coastal flood event could occur annually by 2050, posing major threats to critical infrastructure that surrounds the Bay, including the international airports in Oakland and San Francisco, and placing 270,000 people and $62 billion of development at risk (San Francisco Bay Conservation and Development Commission, 2012). Knowles (2010) also noted that wetlands are particularly vulnerable, as they would require a total sediment input (i.e., organic matter and inorganic sediment) of up to 10.1 Mm^3/year (~2.6 cm/year) by 2100 to keep pace with the higher projections of sea level rise: presently only as much as 0.4 Mm^3/year is actually being deposited (Schoellhamer et al., 2005) while accretion rates of 0.2–0.5 cm/year have kept pace with recent rates of sea level rise (Callaway et al., 2012). Parker et al. (2011) added that the brackish and freshwater tidal wetlands, in particular, will be additionally stressed by higher salinities and temperatures, leading to lower plant productivity and correlative organic input to the wetland, requiring even higher rates of mineral sediment inputs for the wetland to keep pace with sea level rise.

Cloern et al. (2011) downscaled global climate models and linked them to a series of regional physical and ecological models to assess the impact of climate change for the San Francisco Bay region. Using both a low and a high-end emission scenario, they concluded that primary impacts to the San Francisco Bay Coastal System over the next century include reduced fluvial discharge from the Delta, increased Bay salinity, decline in suspended sediment concentration, and a marked increase in the frequency of extreme water levels.

Ganju and Schoellhamer (2010) modeled geomorphic change in Suisun Bay in response to future scenarios of climate change and sediment supply, demonstrating in all cases that net sediment deposition in the shallowest areas did not keep pace with sea level rise. The greater depths decreased wave-induced bottom shear stress and therefore sediment redistribution during the wind-wave season. This suggests that existing intertidal mud flats and tidal marshes may not be sustained in the future.

5. The special issue

As previously described, the San Francisco Bay Coastal System is a complex marine system with powerful waves and tidal currents, intricate estuarine circulation and sediment transport patterns, and significant anthropogenic influences. Several compilations of the physical processes of the Bay and watershed have been published (Conomos, 1979; Hollibaugh, 1996), however, until now, no synthesis of the past 20 years of science has been achieved. In the past 20 years, major wetland loss, seafloor and Bay floor sediment loss, and coastal erosion have been well documented, inspiring considerable work to understand the sources and transport pathways of sand- and mud-sized material, as well as the governing physical processes that control the evolution of the San Francisco Bay Coastal System. At the core of this research is a comprehensive, multi-faceted sand provenance study that includes a series of geochemical techniques, morphometric analyses, bedform asymmetry quantification, numerical modeling, physical process measurements, and faunal distribution analyses, synthesized in a unique approach to establish provenance and transport. This work is complemented by a series of focused efforts to understand fundamental sediment transport processes and circulation patterns at a range of spatial and temporal scales and within specific estuarine environments, including: the exposed outer coast, tidal flats and marshes, the inlet, Bay floor and Bay tributaries.

This special issue of *Marine Geology* is divided into four primary sections:

1) Introduction and framework geology
2) Sand provenance
3) Circulation patterns and geomorphic change
4) Fine sediment transport.

5.1. Section 1 — introduction and framework geology

The introduction explores the relevant research that has informed our present knowledge of the San Francisco Bay Coastal System, including landmark studies by Gilbert (1917), Conomos (1979), Krone (1979), and Porterfield (1980) summarized in this paper, outlines the framework geology of the region (Elder, this issue) and describes the sub-tidal habitats found at the core of the San Francisco Bay Coastal System (Greene et al., this issue). This knowledge has been greatly enriched due to the recent advances in high resolution bathymetric mapping technology. These papers provide the key boundary conditions for a more thorough understanding of the research presented in the subsequent sections.

5.2. Section 2 — sand provenance

After having established a temporal connection between a major reduction in the supply of sediment to San Francisco Bay since the late 19th century (e.g., Gilbert, 1917: Porterfield, 1980; Wright and Schoellhamer, 2004), the pervasive loss of sediment within the Bay (Capiella et al., 1999; Foxgrover et al., 2004; Jaffe and Foxgrover, 2006; Jaffe et al., 2007; Fregoso et al., 2008; Barnard and Kvitek, 2010), the adjacent ebb-tidal delta (Hanes and Barnard, 2007) and open coast beaches (Dallas, 2009; Dallas and Barnard, 2009, 2011; Barnard et al., 2012b), Section 2 presents a series of papers utilizing a wide variety of techniques to quantitatively establish the sources and sinks of beach-sized sand within the San Francisco Bay Coastal System. This section seeks to establish direct links between sediment found throughout the region, including all major drainages, the Bay floor, the open coast seafloor and beaches, and coastal cliffs. Techniques include traditional heavy mineral analysis (Wong et al., this issue) and X-ray diffraction (Hein et al., this issue), coupled with more sophisticated analytical techniques such as the signature of rare earth elements and strontium/neodymium isotopes (Rosenbauer et al., this issue), numerical modeling (Erikson et al., this issue), and nontraditional approaches such as bedform asymmetry (Barnard et al., this issue-a) and biogenic sediment constituent distributions (McGann et al., this issue). By integrating all these techniques (Barnard et al., this issue-b), a highly comprehensive understanding of sand transport sources, pathways, and sinks is established, thereby providing direct evidence for the regional impacts of sediment supply to and sediment removal from the San Francisco Bay Coastal System.

5.3. Section 3 — circulation patterns and geomorphic change

Section 3 explores the complicated feedback between physical forcing, geomorphology and resulting circulation patterns in the San Francisco Bay Coastal System. This includes investigations along the open coast and adjacent to the Golden Gate exploring sediment transport processes at the mouth of San Francisco Bay (Elias and Hansen, this issue) and the influence of changes in the long-term morphologic evolution of the ebb-tidal delta on nearshore processes (Hansen et al., this issue).

5.4. Section 4 — fine sediment transport

Understanding suspended sediment transport in San Francisco Bay, particularly the mud fraction, is essential because it regulates primary productivity (Cloern, 1987), affects water quality (e.g., the availability and distribution of heavy metals: Schoellhamer et al., 2007), and is a primary factor in controlling the formation and erosion of wetlands and intertidal mud flats, crucial to ongoing extensive habitat restoration efforts (Callaway et al., 2012). Section 4 explores the state-of-the-art in our understanding of fine sediment transport, via studies focusing on the sources and supply of fine sediment to San Francisco Bay (McKee et al., this issue), anthropogenic influences on supply (Schoellhamer et al., this issue), and process measurements (Downing-Kunz and Schoellhamer, this issue; Hestir et al., this issue; Manning and Schoellhamer, this issue; Shellenbarger et al., this issue). In addition, Section 4 includes a series of numerical modeling studies that improve our fundamental understanding and representation of the physical processes that drive fine sediment transport, erosion, and deposition (Jones and Jaffe, this issue; Bever and MacWilliams, this issue; van der Wegen and Jaffe, this issue).

6. Summary

Despite the importance of estuaries as a critical physical, biological, and chemical interface between drainage basins and the coastal ocean, there is still a great deal to be learned about how they function, especially in light of the vast direct and indirect anthropogenic influences that have severely altered their functioning throughout human history. In this special issue, we present a series of papers that greatly improve our fundamental understanding of sediment related coastal–estuarine processes through state-of-the-art investigations of one of the most drastically altered estuaries in the world, the San Francisco Bay Coastal System.

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Exhibit F

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The use of modeling and suspended sediment concentration measurements for quantifying net suspended sediment transport through a large tidally dominated inlet

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ABSTRACT

Sediment exchange at large energetic inlets is often difficult to quantify due complex flows, massive amounts of water and sediment exchange, and environmental conditions limiting long-term data collection. In an effort to better quantify such exchange this study investigated the use of suspended sediment concentrations (SSC) measured at an offsite location as a surrogate for sediment exchange at the tidally dominated Golden Gate inlet in San Francisco, CA. A numerical model was calibrated and validated against water and suspended sediment flux measured during a spring–neap tide cycle across the Golden Gate. The model was then run for five months and net exchange was calculated on a tidal time-scale and compared to SSC measurements at the Alcatraz monitoring site located in Central San Francisco Bay ~5 km from the Golden Gate. Numerically modeled tide averaged flux across the Golden Gate compared well ($r^2 = 0.86$, p-value <0.05) with 25 h low-pass filtered (tide averaged) SSCs measured at Alcatraz over the five month simulation period (January through April 2008). This formed a basis for the development of a simple equation relating the advective flux at Alcatraz with suspended sediment flux across the Golden Gate. Utilization of the equation with all available Alcatraz SSC data resulted in an average export rate of 1.2 Mt/yr during water years 2004 through 2010. While the rate is comparable to estimated suspended sediment inflow rates from sources within the Bay over the same time period (McKee et al., 2013-this issue), there was little variation from year to year. Exports were computed to be greatest during the wettest water year analyzed but only marginally so.

1. Introduction

Large tidal estuaries located at the interface between rivers and the ocean provide a wealth of natural resources and are often an economic hub in many parts of the world. A quantitative understanding of sediment delivered to, stored within, and exported from an estuary is important for a number of issues including maintenance dredging of navigation channels, sand mining, light availability for primary productivity, creation and sustainability of tidal wetlands, and the transport of particle-bound nutrients and contaminants (Teeter et al., 1996; Zedler and Callaway, 2001). Although an estuary provides a readily definable control volume where point sources and sinks exist in the form of rivers and the open ocean, it is difficult to determine sediment influx to the system and net flux at the estuary–ocean boundary. This is particularly true for large tidal inlets in regions of modest to high tide ranges where it is not physically or economically feasible to continuously monitor sediment flux, and exchange is complicated by variations in bathymetry, topography, and density driven flows.

San Francisco Bay is the largest estuary on the U.S. West Coast (Conomos et al., 1985), with an aerial extent of 1200 km^2 and is one example where these issues arise. Sediment exchange between the Bay and Pacific Ocean, which occurs across the > 1.5 km wide tidally dominated Golden Gate inlet, is the least well characterized component of the of the sediment budget. On the basis of conservation of mass, net suspended sediment flux through the Golden Gate has been inferred by accounting of sediment inflows to the Bay and change in sediment storage within the Bay (Ogden Beeman and Associates, 1992; Schoellhamer et al., 2005). Net suspended sediment flux was consistently shown to be seaward with net annual rates decreasing from 5 Mt/yr (million metric tons per year) during the 1990–1995 period to 4.2 Mt/yr for years 1995–2002 (Schoellhamer et al., 2005). Inferences of flux through the Gate can also be made from measurements of water discharge and salinity as a surrogate for scalar components obtained by Fram et al. (2007) and Martin et al. (2007). In that

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study, a series of transects across the Golden Gate were made with a boat-mounted ADCP and a suite of towed instruments. The results showed that both density gradients and bathymetry influence ocean–estuary exchange and that overall, exchange of salinity was far less than prior studies had shown (Parker et al., 1972; Largier, 1996). From the measurements they determined that chlorophyll flux was dominated by tidal pumping, accounting for 64–93% of the net dispersive flux. Similar to the sediment budget studies, net advective flux was shown to be seaward.

Efforts directly aimed at quantifying suspended flux through the Golden Gate were done with the use of numerical model simulations to define sediment transport pathways and in situ measurements for estimation of total net suspended flux over two weeks (Hauck et al., 1990; Teeter et al., 1996). Annual net flux was extrapolated from the two-week measurement campaign encompassing a neap–spring cycle coincident with low freshwater input to the Bay. A shortcoming of that approach is that extrapolating the results to encompass much longer time-periods neglects variations in seasonal patterns of sediment delivery and changing hydrology in response to freshwater inputs and annual tide cycle deviations. In this study, the approach of Teeter et al. is expanded upon and the use of measured suspended-sediment concentrations, along with a simple tidal current model is investigated as means of estimating the suspended sediment flux through the Golden Gate. The use of surrogates to quantify sediment flux through estuarine channels has been done previously for smaller and less energetic embayments (Ganju and Schoellhamer, 2006), but not for large estuaries such as San Francisco Bay. To account for the large geographic scope of San Francisco Bay and high-energy exchange through the Golden Gate, a numerical model simulating sediment transport in the Bay–ocean system was calibrated against measured suspended sediment flux across the inlet. The calibrated and validated model was run for a five month time-period coincident with available suspended sediment concentration (SSC) measurements recorded at Alcatraz Island. Simulation results were then used to derive an equation relating measurements at the Alcatraz monitoring station along with the influence of upstream freshwater loading and sediment flux through the Golden Gate.

The remainder of this paper describes the study site, outlines the data and methods employed, presents the results, and concludes with a discussion and conclusion. In the results section, measurements obtained at the Golden Gate are first presented in order to highlight the variability of water and sediment flux across the channel. Numerical model results are then compared to the flux measurements at the Gate and used to explain some of the variability noted in the observations. The third and final results sub-section presents SSC values from the continuous Alcatraz monitoring station, a model for estimation of currents at Alcatraz, and the equation relating Alcatraz SSC and currents to suspended flux at the Golden Gate.

2. Study site

The San Francisco Bay Coastal System is a complex coastal–estuarine system, with often highly energetic physical forcing, including spatially and temporally variable wave, tidal current, wind, and fluvial forcing. The open coast at the mouth of San Francisco Bay is exposed to swell from almost the entire Pacific Ocean, with annual maximum offshore significant wave heights (h_s) typically exceeding 8.0 m, and mean annual $h_s = 2.5$ m (Scripps Institution of Oceanography, 2012). Inside the Bay, wave forcing is less important, except on shallow Bay margins where local wind-driven waves, and occasionally open ocean swell can induce significant turbulence and sediment transport (Talke and Stacey, 2003).

Tides at Fort Point (NOAA/Co-ops station 9414290) are mixed, semi-diurnal, with a maximum tidal range of 1.78 m (MLLW–MHHW, 1983–2001 Tidal Epoch). Due to the large volume of the Bay (spring tidal prism of 2×10^9 m^3) currents are strong at the Golden Gate constriction where peak ebb tidal velocities exceed 2.5 m/s and peak flood currents reach 2 m/s (Rubin and McCulloch, 1979; Barnard, 2007). The strongest tidal currents throughout the other sub-embayments are focused in the main tidal channels. Though far less dominant physical forcing mechanisms compared to tidal forcing, which causes most of the estuarine mixing (Cheng and Smith, 1998), gravitational circulation and freshwater input (1% of the daily tidal flow, ~19% during record flow) are occasionally important during strong stratification events, with the effects most pronounced in the sub-embayments most distal from the inlet mouth (Monosmith et al., 2002).

Freshwater discharge into the Bay is predominantly from the Central Valley watershed, fed through San Joaquin–Sacramento Delta, which enters the Bay at Mallard Island (Figs. 1 and 2B) and historically supplied 83–86% of the fluvial sediments that enter the Bay (Conomos, 1979; Porterfield, 1980; Smith, 1987). Inputs from the Delta are controlled by water operations and reservoir releases, which are strictly managed during the low-flow season (~May–November) to keep the 2-psu isohaline seaward of the Delta. During wet winters, turbid water plumes from the Central Valley watershed have extended into South Bay (Carlson and McCulloch, 1974) and out past the Golden Gate (Ruhl et al., 2001).

The majority of sediment delivered to the Bay has historically been from the Delta (Porterfield, 1980), with nearly all (87–99%) of it in suspension (Schoellhamer et al., 2005; Wright and Schoellhamer, 2005). In recent years, suspended sediment loads from the Delta have diminished in response to ceased hydraulic mining of the 19th Century and other factors (Wright and Schoellhamer, 2004; Singer and James, 2008; McKee et al., 2013-this issue) causing the relative importance of loads from the small 250+ local tributaries to increase. These local watersheds may now account for ~61% of the total suspended load entering San Francisco Bay (McKee et al., 2013-this issue), but are typically episodic such that 90% of the total annual sediment load is released during only a few days (Kroll, 1975; McKee et al., 2006).

San Francisco Bay sediment consists primarily of silts and clays in South, San Pablo, and Suisun Bays and the shallow waters of Central Bay (Fig. 1), while sands dominate in the deeper parts of Central, San Pablo and Suisun Bays and in Carquinez Strait (Conomos and Peterson, 1977). Sediment grain sizes range from 2 μm to 430 μm in the northern embayments (Locke, 1971; Jaffe et al., 2007), from 62 μm to 350 μm in Central Bay (Chin et al., 2010; Barnard et al., 2011), and are on the order of 290 μm at the open coast (Barnard et al., 2007). Due to strong tidal currents, the 113 m deep channel floor at the Golden Gate is void of sediment with exposed bedrock.

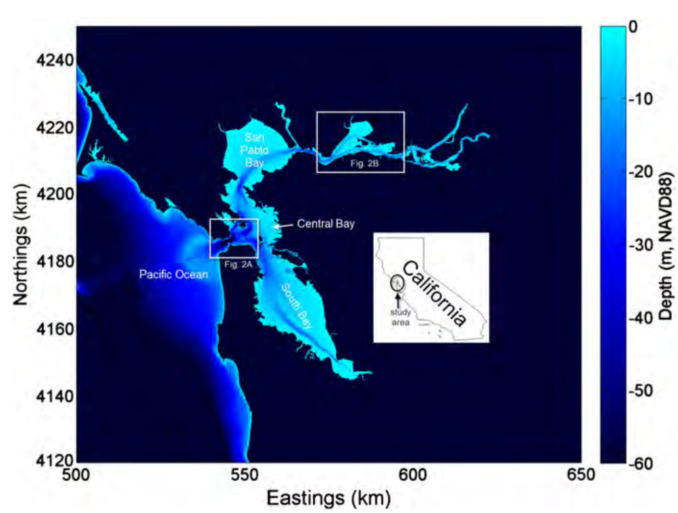

Fig. 1. Site study map showing San Francisco Bay, North and Central Bays, and the Sacramento/San Joaquin Rivers (Delta).

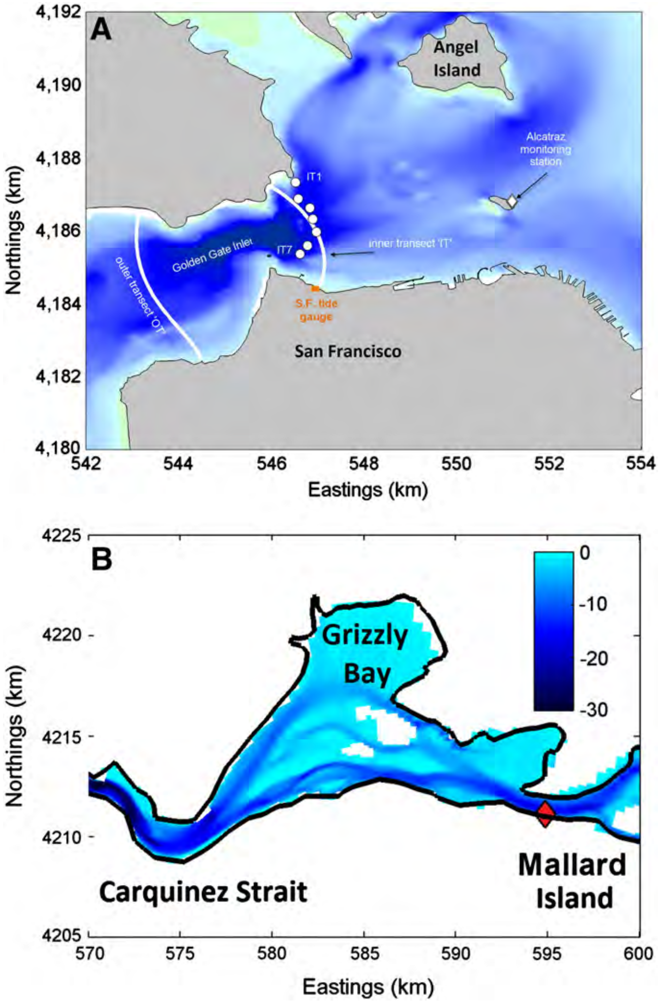

Fig. 2. Studied areas of suspended sediment flux; (A) Golden Gate inlet at the ocean–estuary interface, and (B) Mallard Island at the constriction between the Delta and remainder of San Francisco Bay. Depth shading in A is the same as in Fig. 1.

3. Data and methods

3.1. SSC monitoring

The U.S. Geological Survey operates continuous monitoring of SSC on the northeast side of Alcatraz Island (N37.82722, W122.42167; Fig. 2A) 5 km from the Golden Gate inlet and a second one at the California Department of Water Resources Mallard Island Compliance Monitoring Station (N38.042778, W121.91917; Fig. 2B) located between the confluence of the Delta and Suisun Bay in the northern reaches of S.F. Bay (Buchanan and Lionberger, 2006). The sonde at Alcatraz is positioned approximately mid-way in the water column at ~3 m below mean sea level and consists additionally of a conductivity sensor for inference of salinity concentrations. Two optical sensors continuously monitor SSC in the upper and lower parts of the water column at Mallard Island (total water depth ~8.8 m). In this study, SSC measurements from the upper sensor at Mallard Island were used to represent suspended sediment influx to San Francisco Bay from the Delta region. The upper sensor was used in an effort to reduce the contribution of re-suspended and bed-load material in the measurements. With the exception of data drop-outs due to instrument malfunction or bio-fouling, the Alcatraz and Mallard Island monitoring sites have been operational since November 2003 and February 1994, respectively. Instruments at both sites log one measurement every 15 min. For details on sensor types, calibration, and accuracy see Buchanan and Lionberger (2006).

3.2. Freshwater inflows

Freshwater inflows to San Francisco Bay were estimated with the Dayflow model (CDWR, 2012). Dayflow provides an idealized, unidirectional flow value that is the net water balance of all freshwater inputs and outputs to the Sacramento/San Joaquin River Delta. Daily averaged values between 1956 and 2010 show that maximum flows typically occur during the winter and spring months (January through April) in response to high precipitation events and snow melt, and on average range from 1000 m^3/s to >2000 m^3/s with a peak in late February to early March (Fig. 3). Delta inflow rates were critically low (~500 m^3/s; dashed line and dark shaded area in Fig. 3) in water year (WY) 2008, October 01 2007–September 30 2008, and during the Golden Gate sediment flux monitoring period in January 2008 discussed in the next section. A week prior to the flux measurements, 'normal' inflow rates of 1450 m^3/s were reached for a brief time.

3.3. Vertical profiles of water column properties at the Golden Gate

Vertical profiles of temperature, salinity, velocity and acoustic backscatter (600 kHz RDI ADCP), and volumetric suspended-sediment concentration and grain size (Sequoia Scientific LISST-100X) were collected at seven locations along a transect just inside the Golden Gate (Inner Transect, IT, Fig. 2A, Table 1). Profiles were collected during a neap tide on 17 Jan 2008 and during a spring tide on 24 Jan 2008 (Fig. 4). Tables 2A and 2B summarize the along channel currents (u_{ac}), grain size (gs), salinity, and temperature (S and T) measured at the seven stations for neap (Table 2A) and spring (Table 2B) tides. Point measurements of suspended-sediment concentration (by mass) were made in conjunction with the 17 Jan 2008 profiling in order to estimate floc density and provide a conversion from LISST volume concentration to mass concentration. A USGS P-61 sampler (Edwards and Glysson, 1999) was used to collect 20 samples co-located with LISST profiles, ranging in depth from 3 m to 30 m. Comparison of the P-61 and LISST concentrations (Fig. 5A) yielded a floc density of 1.26 g/cm^3 which is comparable to other published estimates for San Francisco Bay (Krank and Milligan, 1992).

3.4. Moving-boat velocity and backscatter profiling along lateral transects

Three-dimensional velocity and acoustic backscatter data were collected (600 kHz RDI ADCP) from a moving boat (DGPS for positioning) along two transects, one just inside (IT) and one just outside of the Gate (OT) (Fig. 2A). Neap tide measurements were made on Jan 16 (outer) and Jan 17 (inner) while spring tide measurements were made on Jan 23 (outer) and Jan 24 (inner). The water and boat velocity data were used to compute the total water flux through the cross-section using standard techniques for computing discharge from moving-boat ADCP data (Simpson, 2001). Suspended-sediment flux through the cross-section was computed from a similar technique that incorporates calibrated backscatter data from the ADCP. Backscatter intensity data were corrected for beam spreading and water absorption (attenuation due to sediment was determined to be small), then calibrated to SSC using the vertical profile data described above. Concurrent backscatter and calibrated LISST profiles were used to generate the backscatter-SSC calibration (log scale, see e.g. Gartner, 2004) shown in Fig. 5B. This calibration was used to convert backscatter data from the moving boat transects to SSC. The total suspended-sediment flux through the cross-section was then computed by multiplying SSC and velocity in each ADCP bin, then integrating these sediment fluxes over the cross-section in the same manner as for the water flux measurements.

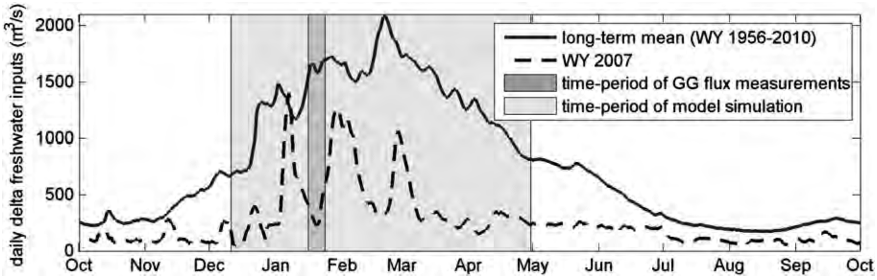

Fig. 3. Net freshwater inflows from the Sacramento/San Joaquin River Delta to San Francisco Bay (California Department of Water Resources, 2012). Darker gray area highlights the time-period in water year (WY) 2008 when flux measurements at the Golden Gate were obtained for this study; lighter gray shading indicates time-period of model simulation. Compared to the long-term mean (solid line), freshwater inputs were low during the flux measurements.

3.5. Numerical modeling

Suspended sediment flux measurements obtained in January 2008 (Sections 3.3 and 3.4) coincided with relatively low seas and swell (max significant wave heights = 2.5 m at the SF Bar buoy, CDIP) and calm meteorological conditions (max winds < 5 m/s, NDBC) and hence only tidal forcing, freshwater, and sediment inputs were used as boundary conditions to model sediment flux through the Golden Gate.

The numerical model Delft3D was used to simulate water and sediment exchange at the Golden Gate (Lesser et al., 2004; Deltares, 2011). The Delft3D package is a modeling system that consists of a number of integrated modules; the ones relevant to this work allow for the simulation of hydrodynamic flow by solving the shallow water equations, and transport of salinity and sediment by solving the advection–diffusion equation.

Given the large spatial extent of the San Francisco Bay system, the model was divided into five two-way coupled domains of varying resolution thus enabling parallel computing and reducing computation time (Fig. 6). Grid resolution ranged from ~50 to 100 m at the Golden Gate inlet and from 100 m to >500 m in the northern reaches of Suisun Bay The Delta was highly schematized as the primary goal was to provide storage of the tidal prism. Tidal variations were driven at the open boundaries of the large-scale ocean domain that extended out past the continental shelf. A total of 12 tidal constituent amplitudes and phases (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, MF, MM, M_4, MS_4, and MN_4) were applied at the open boundary with initial estimates obtained from the TOPEX7.2 global tidal model (Egbert et al., 1994; Egbert and Erofeeva, 2002). Hydrodynamic aspects of the model were calibrated and validated against >30 tide stations throughout the Bay and water flux measurements obtained along the inner and outer transects across the Golden Gate described previously. Details of the numerical modeling approach used in this study, including hydrodynamic model calibration and validation, can be found in Elias and Hansen (2012).

All domains were run in a depth averaged mode (2DH). This approach assumes that flows at the Golden Gate and all other areas are vertically well-mixed and not strongly stratified; a reasonable assumption given that the model simulations were done for a critically dry water year and that there was little vertical variation in measured salinity. If the water column was actually strongly stratified then the 2D model would presumably have significant discrepancies in the predicted fields of both velocity and suspended sediment concentration. Typically the vertical velocity gradients would be larger for stratified flows, and the suspended sediment distribution could influenced by flocculation processes if there was a sharp interface between fresh and brackish water.

Four sediment fractions were simulated in the model; two non-cohesive (sand) and two cohesive. Based on measured grain size distributions at the Golden Gate and previous measurements within Central Bay and outer coast, median sand-sized particles of 200 μm and 350 μm were simulated. A specific density of 2650 kg/m^3 and dry bed density of 1600 kg/m^3 was assumed for all sand fractions; all sand transport calibration parameters were kept at the default values. Sand fraction transport was modeled with the van Rijn TR2004 formulation, which has been shown to successfully represent the movement of non-cohesive sediment ranging in size from 60 μm to 600 μm (Van Rijn, 2007).

Transport of the cohesive mud fractions were modeled with the Krone and Ariathurai–Partheniades formulations (Krone, 1962; Ariathurai, 1974). The critical shear stress for deposition (τ_{crd}) was set to 1000 N/m^2, which effectively implied that deposition was a function only of concentration and fall velocity (Wintwerp and Van Kesteren, 2004). The critical shear stress for erosion (τ_{cre}), fall speed velocity (w_s), and erosion rate constants (M) were treated as calibration parameters. Values in the range of $0.1\ \text{N/m}^2 < \tau_{cre} < 0.4\ \text{N/m}^2$, $0.09\ \text{mm/s} < w < 1.01\ \text{mm/s}$, and $5 \cdot 10^{-5}\ \text{kg/m}^2/\text{s} < M < 2 \cdot 10^{-4}\ \text{kg/m}^2/\text{s}$ were tested based on previous laboratory and modeling studies (Mehta, 1986; Teeter, 1986; Kineke and Sternberg, 1989; Krank and Milligan, 1992; Ganju and Schoellhamer, 2009; van der Wegen et al., 2011a,b). Characteristic parameters of the mud fractions were determined by running numerous simulations with varying sediment size and minimizing observed–modeled differences; the resulting parameters are listed in Table 3. A mid-range dry bed density of 850 kg/m^3 was assigned to both cohesive fractions (Porterfield, 1980). Based on recent field measurements (Manning and Schoellhamer, 2013-this issue), fall speed velocities were kept constant under all salinity concentrations and flocculation was considered to be negligible.

Bed composition maps were generated following guidelines outlined by van der Wegen et al. (2011a,b). In that approach, initial bed composition is estimated by defining sediment availability throughout the domain and then running the model over long time periods to distribute sediments over the domain using prevailing hydrodynamic conditions. The resulting bed composition is then used as the initial condition. In this study, bed thickness maps were constructed from measurements summarized by Chin et al. (2004) and assuming 6 m in areas void of observations. A single layer was used, such that all fractions eroded and deposited onto the same layer. Initial estimates of bed composition were assumed to consist of 100% sand in the ocean domain and at the Golden Gate inlet, 6% cohesive and 94% sand in Central Bay and central channels of north

Table 1
Location and water depth at stations sampled along the inner transect (IT).

Station ID	Lon (DD)	Lat (DD)	Water depth (m)
IT1	−122.47126	37.83215	32.5
IT2	−122.47064	37.82814	51.9
IT3	−122.46781	37.82580	57.1
IT4	−122.46712	37.82309	56.5
IT5	−122.46621	37.81988	50.5
IT6	−122.46843	37.81651	34.9
IT7	−122.47033	37.81450	30.9

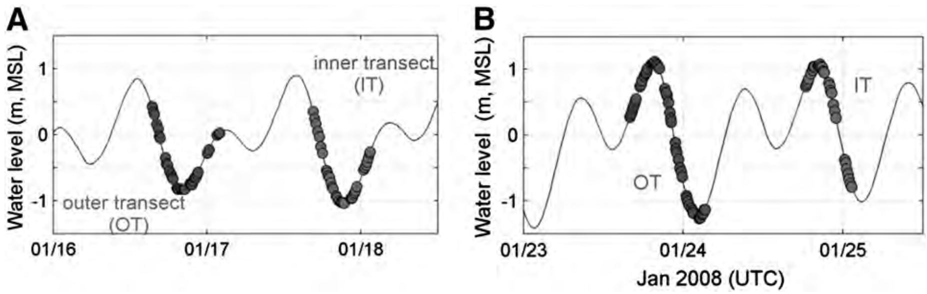

Fig. 4. Time and tidal stage of field measurements obtained during (A) neap and (B) spring tides. Circles indicate times when the vessel was stopped and instrumentation was dropped to measure water quality parameters throughout the water column. ADCP transects were run continuously during the four measurement periods.

and south bays, and 80% and 20% cohesive and sand in the remaining regions of the north and south bays, respectively. The model was then run to simulate ~10 years of sediment re-distribution using a morphological acceleration factor (MorFac) of 100. The use of MorFac values is based on the idea that morphologic changes take place over much longer time periods than hydrodynamic changes and as such, sediment fluxes to and from the bed can be multiplied by a constant MorFac at each morphologic time step in order to decrease the computation time of long-term simulations (Lesser et al., 2004; Roelvink, 2006).

Volumetric Delta flow rates and SSC measurements from the Mallard Island upper gauge were prescribed at the model boundary near Mallard Island to provide daily advective flux of sediment into the model domain. Measured SSCs were averaged over 24 h to coincide with daily Dayflow values representing net freshwater volumetric flow rates from the Sacramento/San Joaquin Delta.

The numerical model was run from December 11, 2007 through April, 2008 to allow for model 'spin-up', encompass the time-period of Golden Gate flux measurements (Section 3.2 to 3.4), and capture some of the variations in measured SSC at Alcatraz. A three week spin up time was prescribed, so that only results from January 01 to April 30 2008 were used in the analysis.

3.6. Flux estimates at the surrogate monitoring site, Alcatraz

In developing a relationship between SSC at the Alcatraz monitoring site and sediment flux through the Golden Gate, estimates of flux rates at the Alcatraz monitoring site were evaluated. The relative

Table 2A
Water column properties measured along the inner transect during neap tide in January 2008.

St. ID	Parameter	Neap tide					
		Upper water column	Mid to upper water column	Mid to lower water column	Lower water column	Min	Max
IT1	u_{ac} (cm/s)	93.1/−6.5	89.3/−10.4	78.4/−5.7	78.1/−10.8	−10.8	93.1
	SSC (uL/L)	27/54	30/57	28/66	29/72	27	72
	gs (μm)	31/41	35/44	40/48	41/58	31	58
	S (psu)	27.9/28.1	27.8/27.5	27.8/27.2	27.3/26.9	26.9	28.1
	T (°C)	10.0/10.1	10.0/10.1	10.0/10.1	10.0/10.1	10	10.1
IT2	u_{ac} (cm/s)	125.0/−38.1	115.8/−42.7	102.4/−50.6	88.0/−63.7	−63.7	125
	SSC (uL/L)	27/58	38/62	40/81	37/122	27	122
	gs (μm)	25/45	37/51	42/74	45/93	25	93
	S (psu)	28.5/29.5	30.8/28.7	30.1/28.5	29.9/28.0	28	30.8
	T (°C)	10.0/10.2	10.3/10.1	10.2/10.1	10.1/10.1	10	10.3
IT3	u_{ac} (cm/s)	120.3/−82.5	112.1/−102.2	102.0/−113.7	96.3/−75.6	−113.7	120.3
	SSC (uL/L)	29/59	46/75	57/138	61/184	29	184
	gs (μm)	42/46	42/50	43/64	41/63	41	64
	S (psu)	30.0/30.0	29.9/29.9	30.8/29.3	29.4/28.5	28.5	30.8
	T (°C)	10.2/10.2	10.2/10.2	10.3/10.2	10.1/10.1	10.1	10.3
IT4	u_{ac} (cm/s)	90.2/−67.8	97.9/−68.3	100.2/−61.4	89.5/−37.4	−68.3	100.2
	SSC (uL/L)	33/71	47 77	57/108	68/121	33	121
	gs (μm)	42/48	47/58	55/77	50/63	42	77
	S (psu)	31.0/29.9	30.9/29.8	29.6/29.3	29.5/28.5	28.5	31
	T (°C)	10.3/10.2	10.3/10.2	10.2/10.2	10.2/10.1	10.1	10.3
IT5	u_{ac} (cm/s)	88.5/−78.3	94.6/−84.6	93.6/−66.7	81.4/−49.8	−84.6	94.6
	SSC (uL/L)	33/88	30/80	41/85	56/131	30	131
	gs (μm)	38/49	42/51	47/53	50/62	38	62
	S (psu)	30.8/29.9	30.8/29.8	30.3/29.6	29.8/29.4	29.4	30.8
	T (°C)	10.3/10.2	10.3/10.2	10.3/10.2	10.3/10.2	10.2	10.3
IT6	u_{ac} (cm/s)	85.4/17.7	82.0/7.8	73.5/−2.9	69.2/−1.5	−2.9	85.4
	SSC (uL/L)	69/77	85/91	97/124	98/144	69	144
	gs (μm)	43/47	40/52	45/56	45/55	40	56
	S (psu)	30.7/28.5	29.6/28.4	29.9/28.3	30.1/28.1	28.1	30.7
	T (°C)	10.3/10.1	10.2/10.1	10.1/10.1	10.2/10.1	10.1	10.3
IT7	u_{ac} (cm/s)	29.9/−13.0	35.6/−16.0	36.0/−11.8	45.9/−10.4	−16	45.9
	SSC (uL/L)	38/70	47/67	55/69	50/111	38	111
	gs (μm)	39/49	41/52	38/50	37/49	37	52
	S (psu)	30.8/30.7	30.7/30.7	28.8/30.7	28.7/30.5	28.7	30.8
	T (°C)	10.3/10.3	10.3/10.3	10.1/10.3	10.1/10.3	10.1	10.3

Notes: Maximum and minimum values separated by a backslash (/). The upper, mid, and lower water columns each represent 25% of the total water depth as listed in Table 1. Reported SSC, *gs*, *S*, and *T* are those that were recorded in conjunction with the maximum ebb and flood velocities. Ebb flows are positive.

Table 2B
Water column properties measured along the inner transect during spring tide in January 2008. See Table 2A for description.

St. ID	Parameter	Spring tide					
		Upper water column	Mid to upper water column	Mid to lower water column	Lower water column	Min	Max
IT1	u_{ac} (cm/s)	138.2/0.07	121.5/0.07	105.4/0.08	86.8/0.06	0.1	138.2
	SSC (uL/L)	64/124	65/123	67/134	68/143	64	143
	gs (μm)	32/37	32/39	36/38	36/42	32	42
	S (psu)	29.9/31.1	30.0/31.1	30.0/31.0	30.0/30.9	29.9	31.1
	T (°C)	10.0/10.2	10.0/10.2	10.0/10.2	10.0/10.1	10.0	10.2
IT2	u_{ac} (cm/s)	106.8/−53.2	119.9/−18.4	100.1/−34.1	73.6/−24.2	−53.2	119.9
	SSC (uL/L)	41/75	39/99	47/91	81/95	39	99
	gs (μm)	34/41	36/40	39/40	39/49	34	49
	S (psu)	30.4/31.4	30.1/31.3	30.0/31.3	30.9/30.7	30.0	31.4
	T (°C)	10.1/10.2	10.0/10.2	10.0/10.2	10.1/10.1	10.0	10.2
IT3	u_{ac} (cm/s)	106.8/−129.2	119.9/−127.1	100.1/−119.4	86.9/−109.1	−129.2	119.9
	SSC (uL/L)	32/63	42/63	52/85	59/97	32	97
	gs (μm)	34/37	35/39	39/41	39/47	34	47
	S (psu)	30.4/31.5	30.1/31.4	30.0/31.3	30.1/31.3	30.0	31.5
	T (°C)	10.1/10.2	10.0/10.2	10.0/10.2	10.0/10.2	10.0	10.2
IT4	u_{ac} (cm/s)	106.8/−166.2	119.9/−148.2	100.1/−125.7	64.1/−100.1	−166.2	119.9
	SSC (uL/L)	37/65	46/64	48/76	58/81	37	81
	gs (μm)	34/37	36/40	38/43	39/44	34	44
	S (psu)	30.4/31.3	30.1/31.2	30.0/31.0	29.7/31.0	29.7	31.3
	T (°C)	10.1/10.2	10.0/10.2	10.0/10.2	9.9/10.2	9.9	10.2
IT5	u_{ac} (cm/s)	112.0/−161.8	119.9/−163.9	100.1/−152.6	64.1/−121.9	−163.9	119.9
	SSC (uL/L)	38/80	40/80	40/86	45/81	38	86
	gs (μm)	37/39	39/41	39/51	39/44	37	51
	S (psu)	30.9/31.0	30.1/31.0	30.0/30.9	29.7/30.9	29.7	31.0
	T (°C)	10.1/10.2	10.0/10.2	10.0/10.2	9.9/10.2	9.9	10.2
IT6	u_{ac} (cm/s)	119.8/−15.3	119.9/0.04	100.1/0.20	87.6/0.19	−15.3	119.9
	SSC (uL/L)	44/90	60/96	62/104	62/108	44	108
	gs (μm)	35/39	36/44	38/45	38/47	35	47
	S (psu)	30.7/31.1	30.1/31.5	30.0/31.4	30.6/31.1	30.0	31.5
	T (°C)	10.1/10.2	10.0/10.2	10.0/10.2	10.1/10.2	10.0	10.2
IT7	u_{ac} (cm/s)	106.8/39.7	119.9/−29.5	100.1/−19.5	73.4/−6.6	−29.5	119.9
	SSC (uL/L)	40/102	53/97	64/129	68/166	40	166
	gs (μm)	35/40	37/41	39/41	39/43	35	43
	S (psu)	30.4/31.4	30.1/30.9	30.0/30.9	31.1/30.9	30.0	31.4
	T (°C)	10.1/10.2	10.0/10.2	10.0/10.1	10.2/10.1	10.0	10.2

importance of different mechanisms contributing to the horizontal sediment flux (F) can be estimated by averaging over a tidal cycle so that (Dyer, 1997):

$$F = \underset{(1)}{[U][A][C]} + \underset{(2)}{U^{'}[A]C^{'}} + \underset{(3)}{U^{'}A^{'}[C]} + \underset{(4)}{U^{'}[A][C]} + \underset{(5)}{[U]A^{'}[C]} + \underset{(6)}{[U][A]C^{'}} + \underset{(7)}{[U]A^{'}C^{'}} + \underset{(8)}{U^{'}A^{'}C^{'}} \quad (1)$$

where U denotes current velocity, A the cross-sectional area through which sediment passes, and C the SSC. The brackets denote cross-sectional time averaged values, and the prime indicates deviations of instantaneous values from tidally averaged values (e.g., $C' = C - [C]$). Tide-averaging was done over 20, 25, 30, and 35 h in order to examine the different tidal time scales over which individual flux terms yield net balances. Low-pass filtering was attained with fourth order forward and reverse Butterworth low-pass filters with frequency cut-offs of 1/20 h, 1/25 h, etc.

The advective and dispersive flux terms (Eq. (1), terms 1 and 2, respectively) typically dominate the total flux, while Stokes drift contributes a smaller portion (Eq. (2), term 3) (Ganju and Schoellhamer, 2006). The advective flux term represents the Eulerian flux and

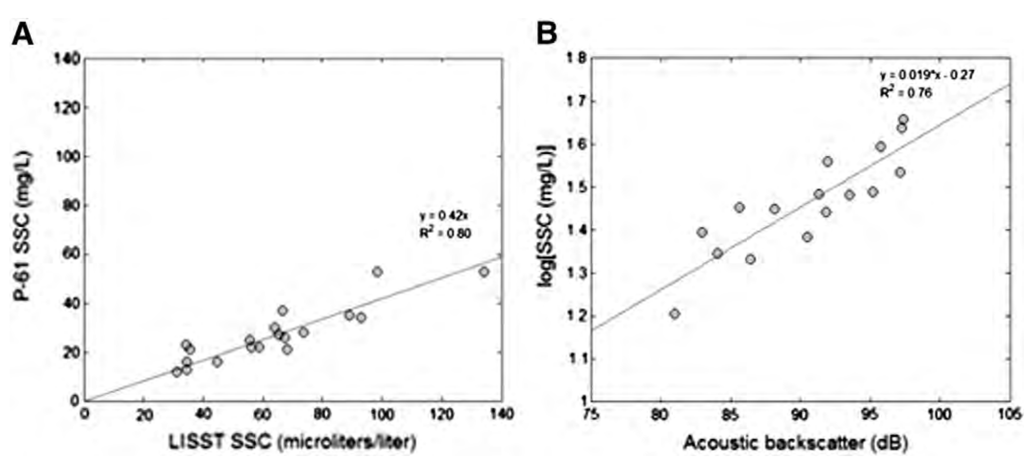

Fig. 5. Calibration curves for (A) mass SSC from water samples versus volumetric SSC from the LISST, and (B) mass SSC from the calibrated LISST versus acoustic backscatter from the ADCP.

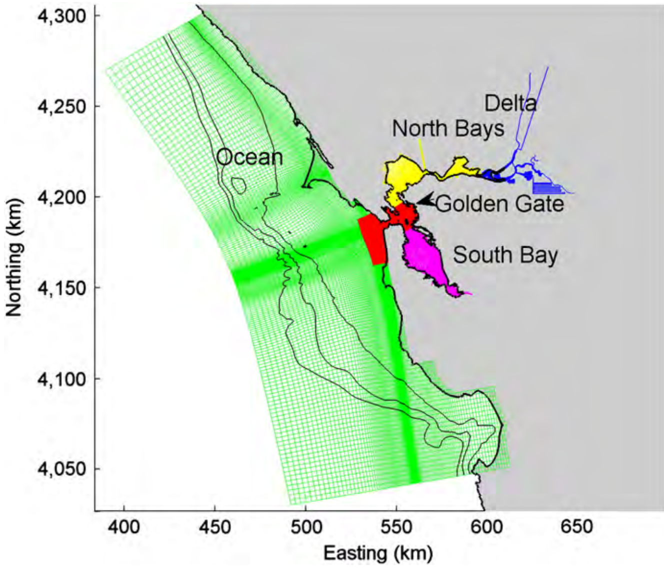

Fig. 6. Curvilinear grids used in the numerical model. A total of five two-way coupled domains were used: Ocean, Golden Gate, North Bays, Delta, and South Bay. Contours are the 100 m, 500 m and 1000 m isobaths.

quantifies the contribution of average discharge and concentration to the total flux, while the dispersive flux represents the correlation between velocity and sediment concentration fluctuations. Stokes drift characterizes the correlation between velocity and cross-sectional area. In this study, the ratio of the cross-sectional area at Alcatraz and the Golden Gate inlet was assumed to be constant, and therefore the Stokes drift term was excluded from further analysis. The remaining terms in Eq. (1) are usually negligible.

With the aim of developing an analytical approach to estimating flux at Alcatraz, a readily useable relationship to estimate currents at this site was required. Because the currents are tidally dominated, harmonic analysis of a velocity time-series computed with the numerical model was done using T_TIDE (Pawlowicz et al., 2002). This provided a set of amplitude and phase values related to dominant astronomic constituents that were used to estimate currents at the Alcatraz monitoring site.

4. Results

4.1. Measurements

4.1.1. Lateral transects

Volumetric rates of water and sediment flux for each of the 25 tracks along the outer and inner transects are summarized in Table 4. As a comparison to a previous study in June 1992 focusing on the transport of dredge material (Teeter et al., 1996), a piece-wise linear regression was fit to the data (Fig. 7). A linear fit through the flood- and most of the ebb-directed transports resulted in a slope of 0.033 and 0.013 for the January 2008 and June 1992 study periods, respectively. Of note is the difference in the cut-off position and slope for the fit of the strongly ebb directed flows. Teeter et al. observed a break in the data at ebbing flows of 50k m^3/s while the data collected as part of this study (January 2008) is only supported by three points and shows that ebb flows in excess of 120k m^3/s yield a change in the sediment flux rate. The difference might be due to sampling protocol, measurement errors, availability of sediment, and variations in volumetric water flux between the two sampling periods. Measurements at the Fort Point tide gauge indicated that the tide range was 30 cm greater during the January 2008 study compared to the June 1992 Teeter et al. (1996) study.

Table 3
Cohesive sediment parameters.

Parameter	Mud-2	Mud-4
Erosion parameter (M, kg/m^2/s)	5.5E−5	1.3E−5
Settling velocity (w, mm/s)	3.0E−1	1.0E−1
Critical bed shear stress for erosion (τ_{cre}, N/m^2)	5.0E−1	1.35E−1

The range of flux rates along both the inner and outer transects (Table 4) varied substantially and highlights the importance of integrating flux rates over full tide cycles. Such intense field campaigns are rarely practical and as such the use of numerical modeling, as was done for this study, offers an approach to filling in time and spatial gaps.

Two transects were chosen to illustrate the distributions of velocities along the inner transect during flood and ebb tides. Two measurements were made during spring tide that had large and comparable ebb and flood water and sediment fluxes, the first and fourth inner transects on Jan 24 (17:44 and 23:05, see Table 4). Water flux was ~90,000 m^3/s and sediment flux was ~3000 kg/s for both transects; the first transect was in the flood direction and the fourth transect was ebb directed. Fig. 8 shows the along channel and across channel velocity contours for the two transects. The east–north velocity vectors were rotated about the transect axis which was ~140° from due east, to obtain along and across channel values. Distances across the channel are from the south bank. The along and across channel flood velocities (Fig. 8 right panels) illustrate what might be the formation of lateral eddies along both channel banks during flood tide. Along-channel flood contours contain regions of positive (ebb directed) flow at both channel margins. Also, across channel flood contours indicate flow toward the north bank (red contours) in the north part of the channel and flow toward the south in the south part of the channel. Ebb tide flow structures (Fig. 8, left panels) are substantially different from flood tide, with along channel velocities being positive and out of the Gate throughout the cross section. Also, across channel velocities illustrate topographic steering effects as flow approaches the Golden Gate constriction, i.e. velocities in the north part of the channel are directed toward the south and velocities in the south part of the channel are directed toward the north. These ebb and flood flow structures are also present in the numerical modeling results presented below.

4.1.2. Point measurements (profiles)

Spring tide flood measurements revealed mid to upper water column velocities that ranged from still water to 164 cm/s (Tables 2A and 2B). Flood directed velocities were never measured at the northern-most station, IT1, and only in the upper water column of IT6. These 'outlier' measurements are likely an artifact of the sampling locations.

SSC concentrations and median grain sizes (*gs*) from the LISST (rmse 7.1 mg/L) exhibited variability both laterally across the channel and vertically with depth. Fig. 9 presents the lateral distribution of depth-averaged SSC for profile measurements that were made immediately following the ebb and flood transects described above and presented in Fig. 8 (both during spring tide). Ebb tide SSC was greatest at the southern-most station and decreased across the channel to the north. Flood tide SSC was more evenly distributed, with the lowest SSC in the middle of the channel and the higher SSC near both banks. Median grain sizes exhibited minimal lateral variability during both ebb and flood tides, with all stations within ~10% of the mean. Also, the mean grain size was comparable during ebb and flood tide (~40 μm).

Fig. 10 shows the vertical distribution of laterally-averaged SSC and median grain size for the same ebb and flood tides as Figs. 8 and 9. For each tide, data from all seven stations were averaged to obtain the laterally-averaged values. SSC tended to be greatest near the bed and decrease toward the surface (Fig. 10, top panels). SSC profiles

Table 4
Measured water and sediment flux rates across the Golden Gate.[a]

Transect	Start time (UTC)	End time (UTC)	Start tide (m)	Water flux (m^3/s)	Sediment flux (kg/s)
Neap tide					
Outer	1/16/08 14:41	1/16/08 15:28	0.382	59,800	1800
	1/16/08 16:47	1/16/08 17:18	0.80	122,200	4000
	1/16/08 18:43	1/16/08 19:14	1.00	87,100	2800
	1/16/08 20:30	1/16/08 21:11	0.93	20,400	730
	1/16/08 23:06	1/16/08 23:46	0.70	(67,700)	(2000)
	1/17/08 2:05	1/17/08 2:39	1.10	(50,900)	(1600)
	1/17/08 2:44	1/17/08 3:18	1.27	(28,800)	(920)
Ebb range				20,400–122,200	730–4000
Flood range				(28,800)–(67,700)	(920)–(2000)
Inner	1/17/08 16:06	1/17/08 16:34	0.32	69,100	2000
	1/17/08 18:09	1/17/08 18:31	0.84	97,400	3100
	1/17/08 19:47	1/17/08 20:07	1.09	87,100	2800
	1/17/08 21:31	1/17/08 21:56	1.09	33,800	1100
	1/17/08 23:25	1/17/08 23:50	0.90	(24,800)	(990)
Ebb range				33,800–97,400	1100–3100
Flood range				(24,800)	(990)
Spring tide					
Outer	1/23/08 15:21	1/23/08 16:01	0.53	(62,300)	(2300)
	1/23/08 16:55	1/23/08 17:28	−0.11	(107,300)	(3600)
	1/23/08 18:41	1/23/08 19:15	−0.31	(80,800)	(2600)
	1/23/08 20:32	1/23/08 21:10	0.18	26,400	890
	1/23/08 22:15	1/23/08 22:44	0.90	122,700	4800
	1/23/08 23:52	1/24/08 0:50	1.44	128,500	6200
	1/24/08 1:30	1/24/08 2:19	1.67	84,800	3300
	1/24/08 3:16	1/24/08 3:45	1.37	13,900	560
Ebb range				13,900–128,500	560–6200
Flood range				(62,300)–(107,300)	(2300)–(3600)
Inner	1/24/08 17:44	1/24/08 18:06	0.07	(89,100)	(3000)
	1/24/08 19:54	1/24/08 20:08	0.06	(59,400)	(1800)
	1/24/08 21:15	1/24/08 21:35	0.45	5000	240
	1/24/08 23:05	1/24/08 23:22	1.15	93,500	3100
	1/25/08 1:23	1/25/08 1:39	1.73	83,600	3100
Ebb range				5000–93,500	240–3100
Flood range				(59,400)–(89,100)	(1800)–(3000)

[a] Negative (flood) values shown in parenthesis.

were very similar during ebb and flood tide conditions. Median grain sizes showed little variability with depth, similar to the lateral distributions. Again, median grain sizes were comparable between ebb and flood tide and varied little from the mean value of ~40 μm.

4.2. Model simulations

4.2.1. Comparison of modeled and measured water and sediment flux

Measured and modeled cross-sectional averaged volumetric water flux compare very well ($r^2 = 0.98$, Fig. 11A; see also Elias and Hansen, 2012 for further comparison). Employing optimized sediment calibration parameters (Table 3), the sediment mass flux rates also compare well with measurements and explain ~93% of the variance (Fig. 11B). The greatest discrepancy is at peak spring tide along the outer transect where the model over-estimates net outward flux. Only simulation results from the inner transect were used for development of the relationship between Alcatraz SSC and flux at the Gate in this study.

Cross channel observations in Fig. 8 were depth-averaged and compared to model simulated currents in the along and cross channel directions for ebb and flood tides (Fig. 12). The change in current direction across the channel is evident in both the observed and

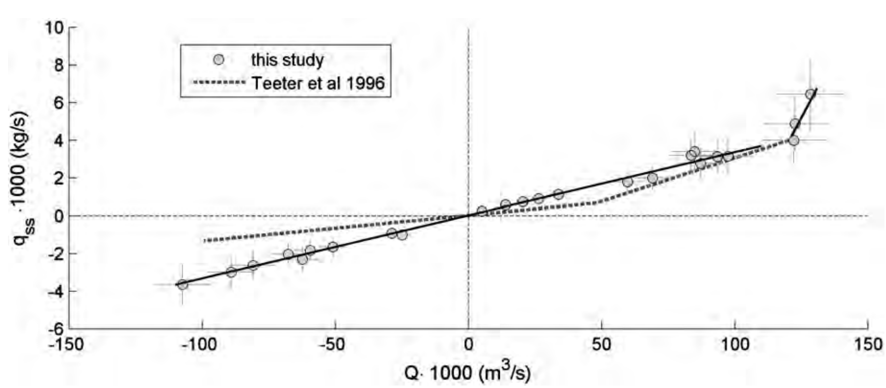

Fig. 7. Measured mass sediment and volumetric water flux across Golden Gate as measured in this study and by Teeter et al. (1996). Piecewise linear regressions for ebb and flood are shown with the solid line for the data collected in 2008. Cross-hairs denote 10% and 30% uncertainty in volumetric water flux (Q) and mass sediment flux (q_{ss}) measurements, respectively.

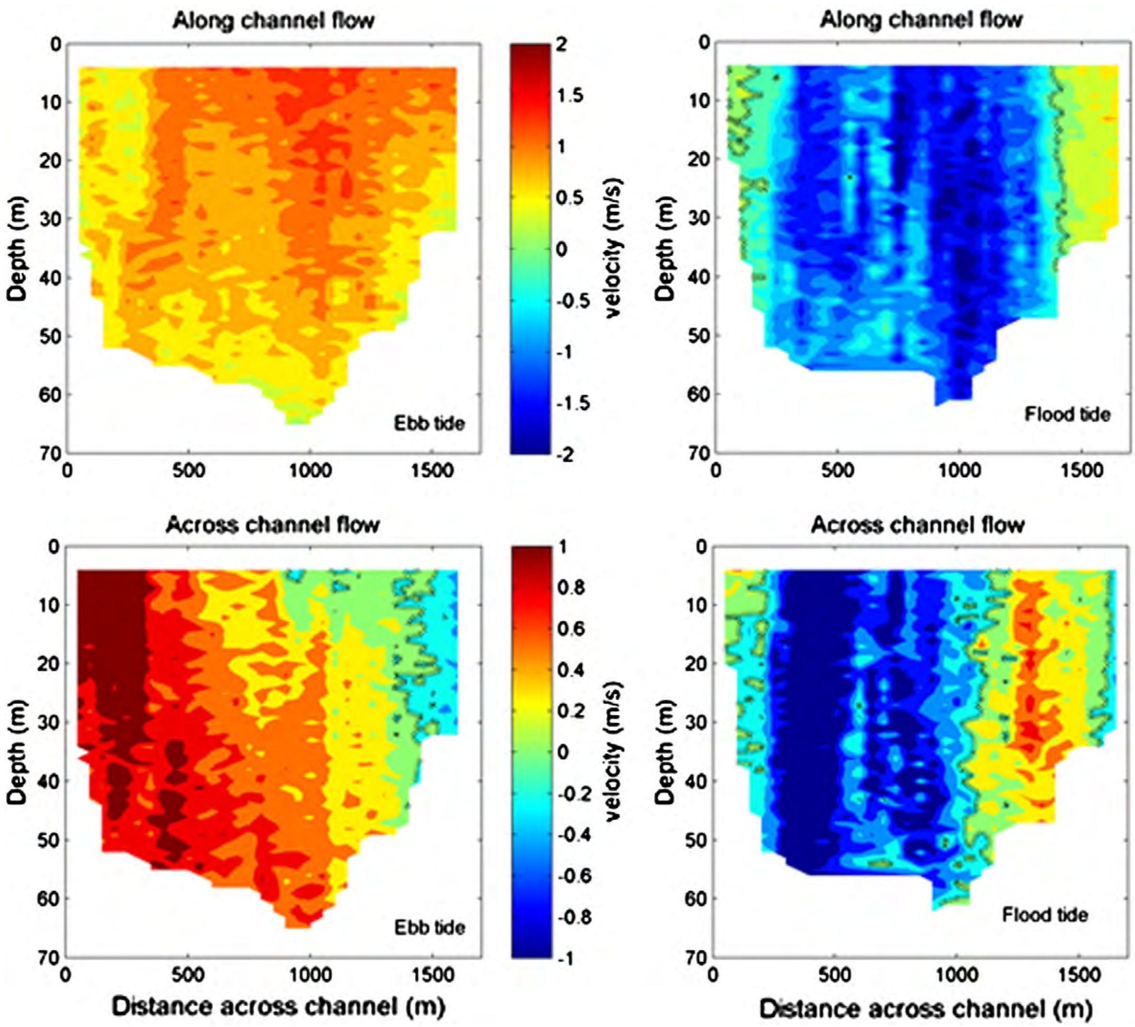

Fig. 8. Contours of along channel (top) and across channel (bottom) velocities (m/s) for ebb (left) and flood (right) tides. Transects shown are from Jan 24, 17:44 (flood) and 23:05 (ebb), see Table 3. Black dashed lines are the zero velocity contours. Along channel, positive values (red) denote ebb direction and negative values (blue) denote flood direction. Across channel, positive values (red) denote flow toward the north and negative values (blue) denote flow toward the south. Note the difference in color scale between the along channel (top) and across channel (bottom) panels.

simulated results, particularly for the cross channel ebb tide case (Fig. 12A). The flow reversal was not as apparent in the model results for the flood event shown in Fig. 12, but was present at other times.

4.2.2. Tidally-varying eddies affecting sediment transport patterns

Model-simulated sediment transport patterns for various stages of the tide illustrate the spatial variation in transport rates across the Golden Gate inlet (Fig. 13). There is significant lateral variability in the instantaneous flux across the inlet; an observation noted by Fram et al. (2007), Fram (2005) and Martin et al. (2007) based on measurements and analysis of chlorophyll and salt flux through the Golden Gate. Fram (2005) and Fram et al. (2007) showed the presence of a tidally trapped counter-clockwise eddy that forms during the second half of the flood tide between Point Cavallo and Angel Island. As the tide decelerates, the eddy moves out into the channel near the end of flood tide. These patterns are also evident in model simulations conducted for this study (Fig. 13B and C). In addition to the tidally trapped eddy east of Point Cavallo, the model also indicates the formation of eddies landward (east of) of Fort Point and the point across the Golden Gate at the south and north terminus of transect IT (Fig. 13A and B) during the flood tide. During ebb tide, the pattern is translated to the seaward side of the Points such that a counter-clockwise eddy forms at Baker Beach west of Ft. Point and smaller clockwise eddy at Bonita Cove at the north end of the channel (Fig. 13D; Fig. 8, Elias and Hansen, 2012). From this it can be seen that neither point measurements nor short term flux estimates are sufficient to accurately describe the net flux at Golden Gate which is subject to strong tidal currents, diurnal asymmetry, and complex bathymetry. Furthermore, instantaneous flux (Fig. 13F) is orders of magnitude greater than the net flux (as shown later), and requires integration with respect to both time and space in order to obtain an accurate estimate of the total net flux.

4.3. SSC monitoring as a proxy to Golden Gate suspended sediment flux

4.3.1. SSC at the Alcatraz monitoring site

Instantaneous SSC at Alcatraz is strongly modulated by tides and to some degree, sediment flux into San Francisco Bay via the Delta. The periodic signal of the Alcatraz SSC time-series suggests variations in concert with semi-diurnal and spring–neap tide cycles (Fig. 14A). A power spectral density estimate of SSC measured at Alcatraz (155 days, $f = 0.001$ Hz, Welch, NFFT = 1024) yields peaks at 10.8 days, 25.8 h, and 12.3 h, similar to peak frequencies of tide-induced water levels at the nearby San Francisco tide gauge (dominant peaks at 21.3 days, 23.81 h, and 12.49 h). The peaks at 12.3 and 25.8 h are related to the dominant tide signal, M_2 ($f = 0.0805\ h^{-1}$) while the 10.8 day periodicity reflects the spring–neap cycles. Highest SSCs at Alcatraz were measured in early to mid-January (Fig. 14A and

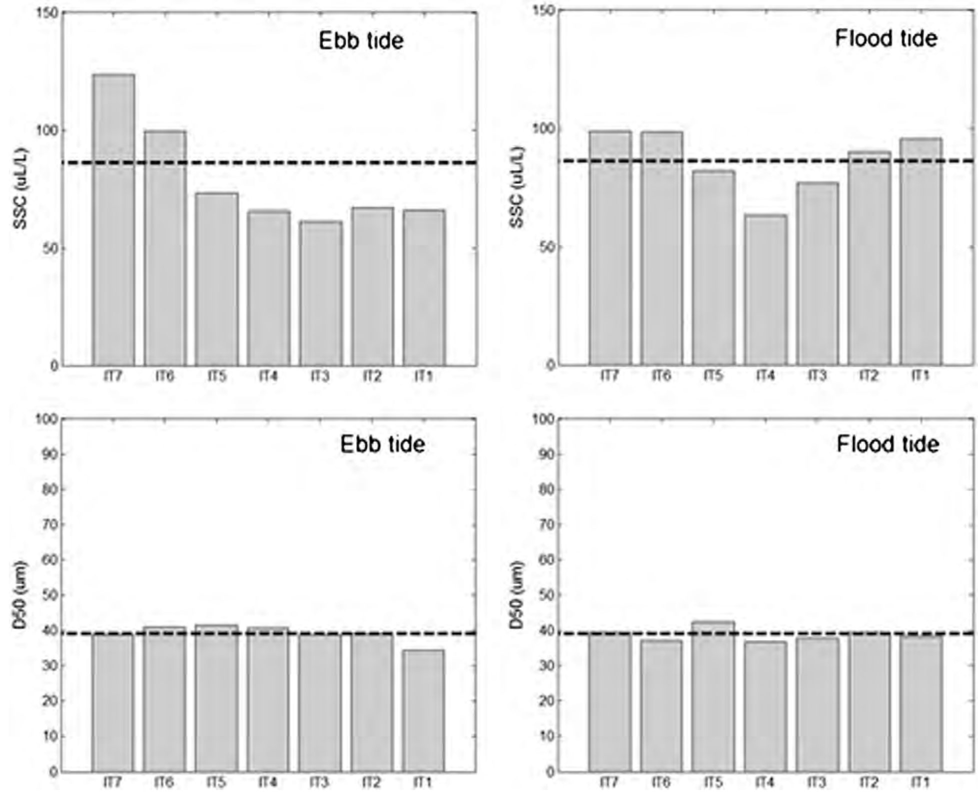

Fig. 9. Lateral distributions of depth-average SSC and median grain size for ebb and flood tides. Measurements were made immediately following the transects shown in Fig. 8. Black dashed lines indicate the mean values for the data in each panel.

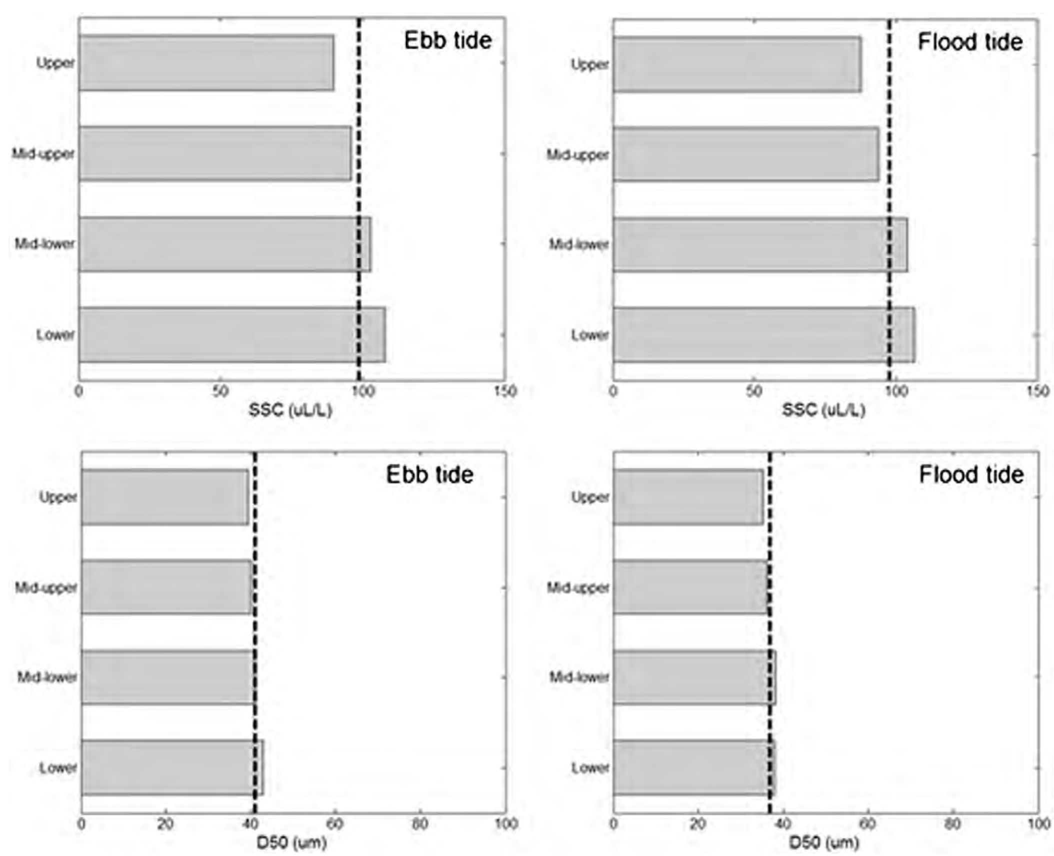

Fig. 10. Vertical distributions of laterally-averaged SSC and median grain sizes for ebb and flood tides. Measurements were made immediately following the transects shown in Fig. 8. Black dashed lines indicate the mean values for the data in each panel.

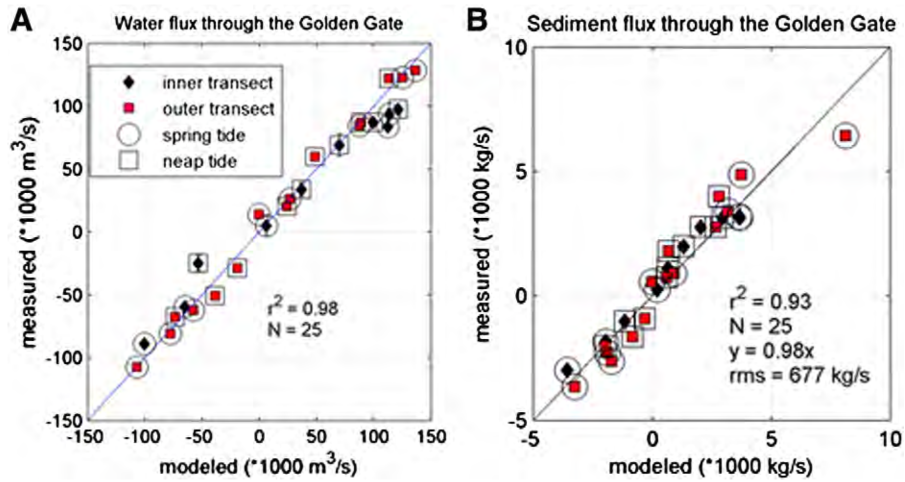

Fig. 11. Comparison of modeled and measured (A) water discharge and (B) suspended flux through the Golden Gate. Solid line in (A) depicts perfect fit; solid line in (B) depicts best fit linear line with zero y-intercept.

C) and coincided with the highest tides of the year (perigee lunar alignment). Concentrations are highest during the transition from ebb to flood of the lower low stage of the tide (Fig. 14C).

Upon initial inspection of the time-series SSC data, a clear dependence of Alcatraz sediment concentrations to measured SSC at the Mallard Island monitoring site is not evident. A more direct comparison of sediment loads with Alcatraz SSCs elucidates the relationship. The daily advective sediment load from the Delta was estimated with the product of daily averaged Mallard Island SSCs and Delta freshwater inflows from the Dayflow model. The load estimate may be somewhat of an over-estimate as the landward dispersive load was not accounted for, which might reduce the amount by ~20% of the total (McKee et al., 2006), but overall the estimate should be reasonable. Cross-correlations indicate a delay of 8 days or more in the response of the Alcatraz SSC measurements to sediment loading from the Delta. A 12 day lag of the Alcatraz SSC data suggests a linear trend with sediment loadings <3000 t/day (Fig. 14D), while at greater loading rates the sediment plume appears to migrate down-estuary somewhat quicker (8 day lag; inset Fig. 14D). Although the correlations between sediment loading and SSC measurements at Alcatraz are weak ($r^2 =$ 0.14 for loadings <3000 t/day and $r^2 < 0.1$ for higher loading rates), visual inspection of the lower bounds indicate an increase in daily averaged SSC at Alcatraz in response to increased sediment loads at Mallard Island. The low correlations, which represent a linear least square fit through all the data, are likely due to the unusually low sediment influx to the system during WY08 and concealment of the signal at Alcatraz by SSC from other sources and processes that are of equal or greater magnitude. It is expected that similar analysis of data from 'normal' water years would show a greater dependence of SSC at Alcatraz to advective sediment loads from the upper reaches of North Bay.

4.3.2. Currents at the Alcatraz monitoring site

The tidal ellipse of numerically modeled currents at Alcatraz was bi-directional with an ebb preference (Fig. 15A). Harmonic analyses indicate that east- and north-directed velocities can be well represented with six tidal constituents (Table 5). Re-construction of the tidal currents for the time-period spanning January 01–April 30 2008, using T_TIDE and the tidal amplitudes and phases listed in Table 5 resulted in *rms* errors = 0.11 m/s and 0.12 m/s for the east- and north-directed currents, respectively (Fig. 15B).

A time-series of current magnitudes computed with the numerical model is plotted in Fig. 16A. A positive or negative value was assigned for ebb or flood, respectively, based on the orientation of the tidal ellipse defined in Fig. 15A. The low-pass filtered (tide-averaged) signal is shown with the solid black line and is mostly positive illustrating the net ebb directed flow. The low-pass filtered signal is repeated in Fig. 16B and compared to the time-series reconstructed from tidal constituents. The reconstructed time-series compares well with the full low-pass filtered signal, and forms the basis for computing advective and dispersive flows at Alcatraz that are used in the development of the relationship linking surrogate measurements at Alcatraz with suspended sediment flux at the Gate.

4.3.3. Sediment flux at the Golden Gate

In developing an analytical relationship whereby measurements can be used to estimate the net sediment flux at the Golden Gate,

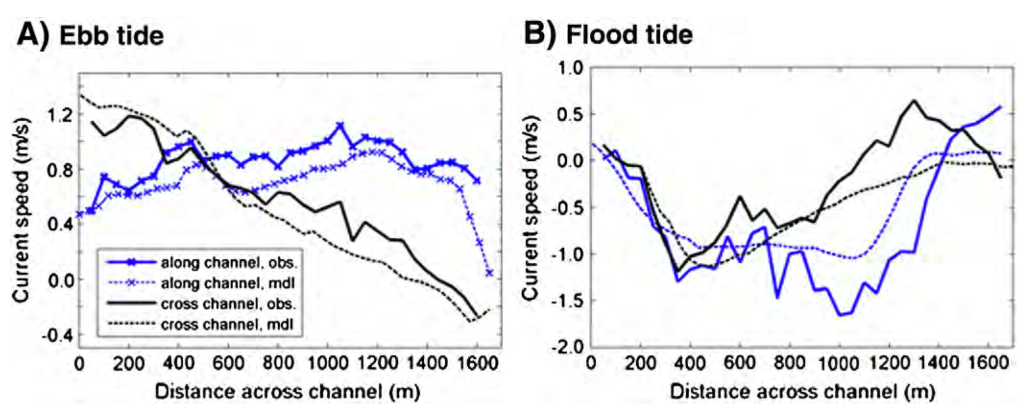

Fig. 12. Comparison of modeled and measured depth-averaged velocities across the channel for (A) ebb and (B) flood conditions shown in Fig. 8.

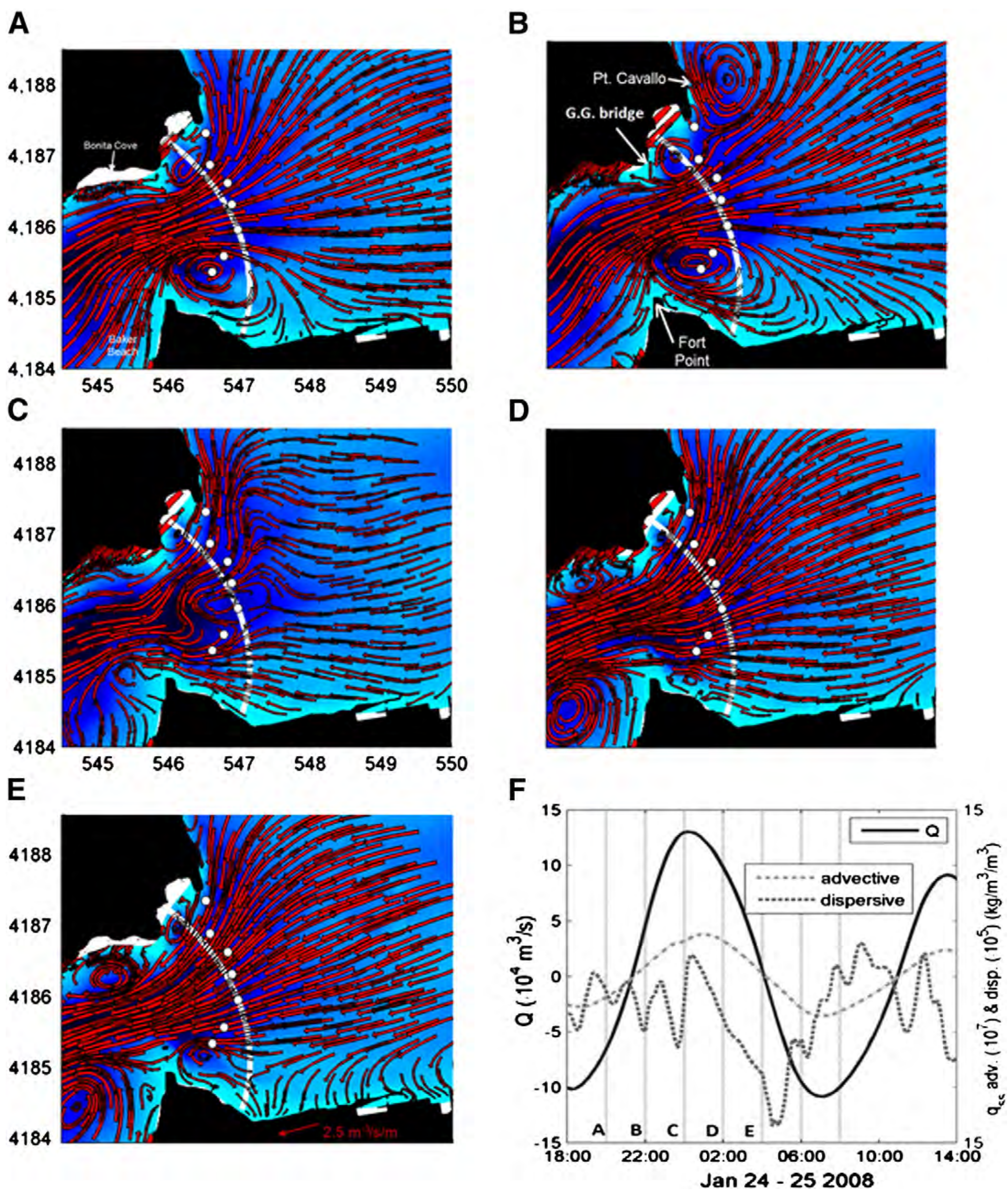

Fig. 13. Modeled sediment transport streamlines during various stages of the tide. Tidal stage is illustrated in subplot (F) with vertical dashed lines. Instantaneous volumetric water and mass advective and dispersive sediment flux are shown with the curved lines. The scale for dispersive flux is 100 times smaller than that for advective flux so its variability can be seen on the graph.

the two primary flux terms (advective and dispersive) in Eq. (1) were computed with Alcatraz observation data and plotted against tide-averaged total suspended sediment flux at the Golden Gate (January through April 2008) for tide-averaging periods of 20 h, 25 h, 30 h, and 35 h. While three of four tide-averaging periods for the dispersion term (Eq. (1), term 2) were statistically significant, coefficients of determination (r^2) were all less than 0.05 (Table 6). The advection term was statistically significant (p-value <0.05) for all tide-averaging periods tested and yielded r^2 values ranging from 0.52 (35 h tide-averaging) to 0.86 (25 h tide-averaging). Instantaneous and 25 h tide-averaged sediment flux at the Golden Gate are shown in Fig. 17.

A scatter plot of low-pass filtered (25 h) suspended sediment flux at the Golden Gate compares well with the low-pass filtered Alcatraz advective term ([*SSC*][*U*], Fig. 18). Least-squares fits between the data yielded a linear and second order polynomial relationship of about equal goodness-of-fit ($r^2 = 0.86$, rmse = 67.2 kg/s and $r^2 = 0.87$, rmse = 66.3 kg/s, respectively). As the second-order polynomial is only marginally better, we have chosen to employ the linear fit describing flux at the Gate with SSC,

$$F_{GG} = 1.21 \cdot 10^5 \cdot [SSC] \cdot [U] + 40.3 \quad (2)$$

where F_{GG} (kg/s) is the 25 h low-pass (tide-averaged) filtered suspended sediment flux at the Golden Gate, [*SSC*] is the measured tide-averaged suspended sediment concentration at the Alcatraz monitoring site (kg/m^3), and [*U*] the tide-averaged currents (m/s) computed from tidal constituents in Table 5.

Application of Eq. (2) with Alcatraz SSC data for water years 2004 through 2010 resulted in predominantly seaward directed sediment flux (Fig. 19). Net 25 h averaged flux rates were typically <800 kg/s but reached nearly 1500 kg/s in early 2006 coincident with high

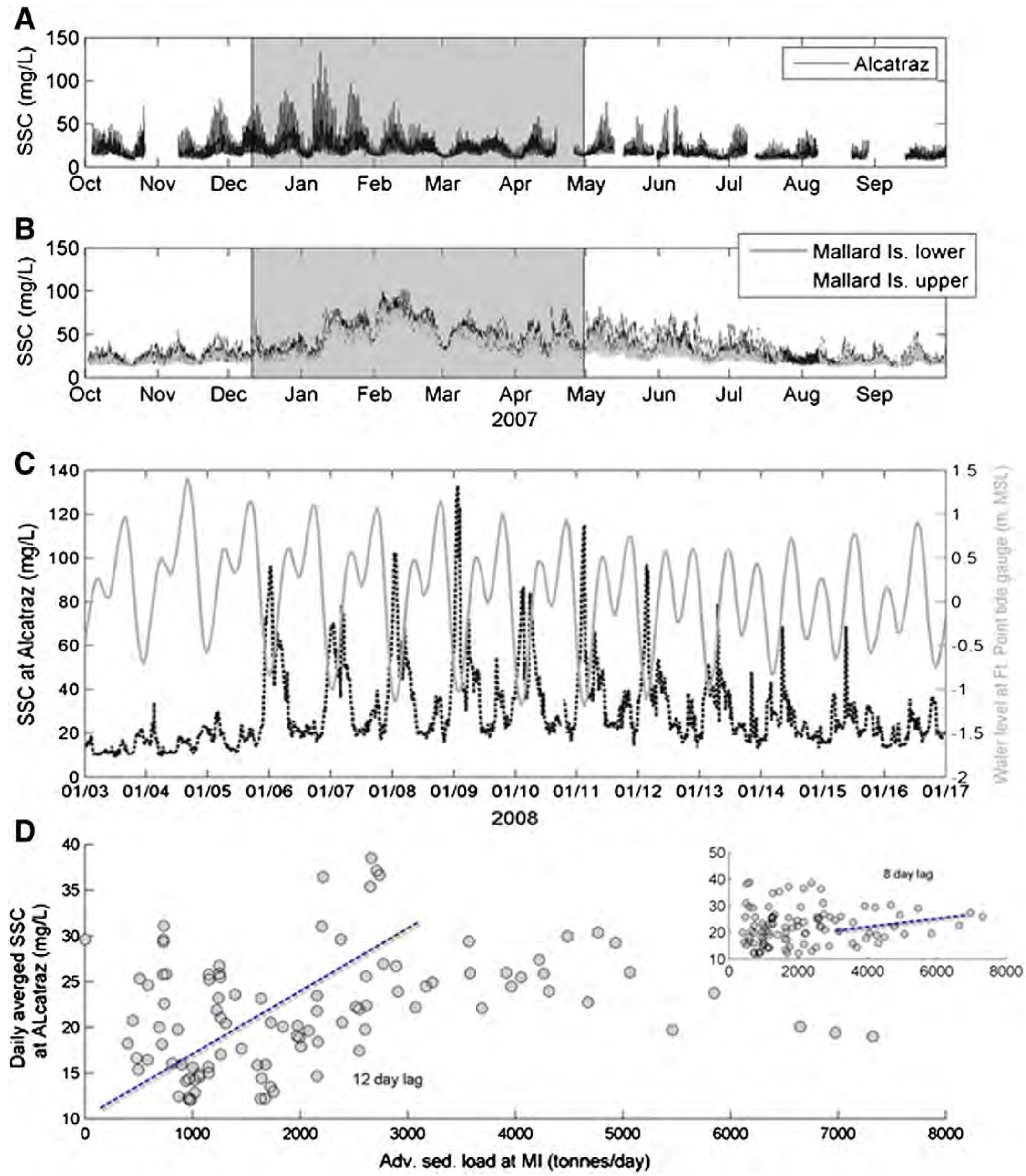

Fig. 14. Suspended sediment concentrations at Alcatraz and its relation to the tide regime and sediment load from the Delta. (A and B) Instantaneous suspended sediment concentration (SSC) for water year 2007 (October 01, 2007 through September 30, 2008) at Alcatraz and Mallard Island. Gray shaded areas denote time-period simulated with the numerical model. December to January simulation results excluded from analyses as this time-period was used for 'model spin-up'. (C) Tide-averaged SSC at Alcatraz shows a relatively strong correlation with the tide-range measured at the nearby Ft. Point San Francisco tide station. (D) Instantaneous measured SSC at Alcatraz and water level at the tide station illustrates the coincidence of a higher tide range and low water levels with elevated SSCs. (E) Daily averaged SSC at Alcatraz plotted against the inferred sediment load from the Delta at Mallard Island (January through April 2008).

Delta flows. Total net annual flux ranged from 1.1 Mt (million metric tons) to 1.3 Mt with a mean rate of 1.2 Mt. The highest rate was in WY2006 and coincided with the peak and high Delta flows in January 2006 (Fig. 19). Tide periods with incomplete SSC data were filled in with mean values representative of each water year. Water year 2010 had the lowest number of complete tide-cycles with nearly half missing.

5. Discussion

The study period, determined by the timing of the sediment flux measurements at the Golden Gate obtained as part of this study, happened to coincide with a critically dry water year. Using satellite images from 1995, Ruhl et al. (2001) showed that sediment plumes can extend from the Delta to >10 km seaward of the Golden Gate during high Delta inflows, while during low flows (~1700 m^3/s), a plume is barely discernible south of San Pablo. The maximum Delta flow rate achieved during the WY08 study period was 1500 m^3/s and comparable to the low flows of the satellite imagery. The relatively insignificant contribution of point source sediment exchange at the Golden Gate calculated with the model and weak correlation between the point source load and measured SSC at Alcatraz is thus not surprising. A question that remains is if the predictor equation (Eq. (2)), developed under conditions of very low flow and sediment loading conditions, is valid for higher freshwater flows and sediment loads. Two primary questions need to be addressed in order for the relationship to hold: 1) do Alcatraz SSC measurements sufficiently reflect the total sediment load available for exchange at the Golden Gate

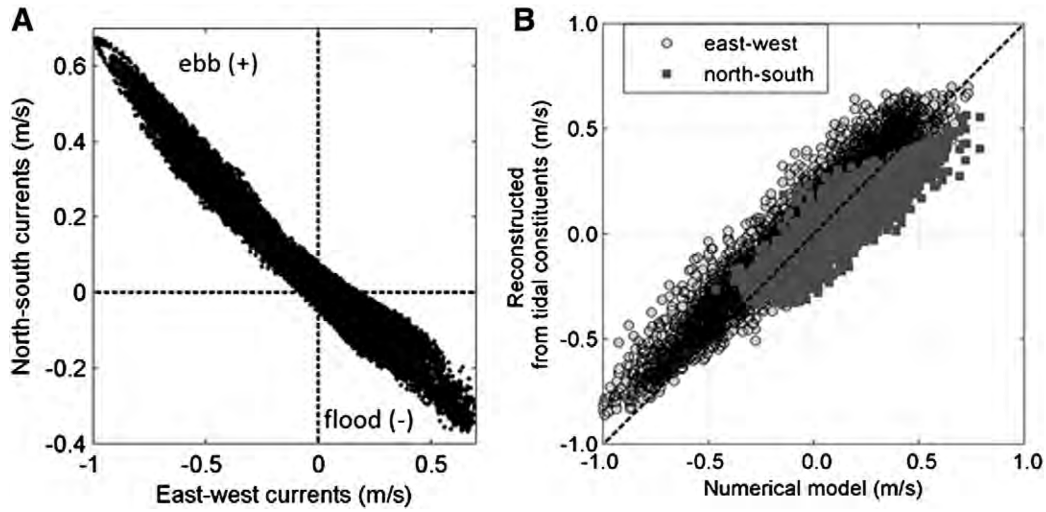

Fig. 15. Modeled hourly depth-averaged currents at Alcatraz. (A) Tidal ellipse at the Alcatraz monitoring site is oriented in the northwest/southeast direction. Ebb is defined as positive. (B) Reconstructed currents calculated with tidal constituents listed in Table 5 plotted against numerically modeled currents at Alcatraz. Dashed line depicts perfect fit.

(from all sources within the Bay), and 2) does the relationship sufficiently account for changes in flow regime in response to high freshwater loadings?

Comparison of the SSC record at Alcatraz (calendar years 2004 to 2010) with Delta flows shows that SSC measurements do reflect inputs from the Delta at high flow rates (Fig. 20). Least-squares linear fits of all available tide-averaged data yields $r^2 = 0.17$ ($N = 1416$). At higher Delta flow rates >3000 m^3/s, the SSC response is substantially more evident ($r^2 = 0.42$; inset of Fig. 20). The seemingly random SSC values below 50 mg/L does include the signal from the Delta as shown previously, but is masked by re-suspended material, sediment that is kept in suspension and transported due to persistent tidal and other currents, and loadings from other sources at the boundaries of the Bay (e.g., tributaries and open ocean boundary). Because the Alcatraz monitoring site is located in Central Bay at the confluence of both the northern and southern reaches of San Francisco Bay, elevated SSC values that correlate well with Delta flows above the 3000 m^3/s threshold likely also reflect loadings from other tributaries that supply sediment during times of high precipitation events. This can be important as the sediment yield from the Delta decreases in response to the ceased 19th Century hydraulic mining era and the relative contribution of sediment supply from other sources increases (McKee et al., 2013-this issue). Linkages between other sediment sources and measured SSCs at Alcatraz have not yet been investigated but would provide useful information for the assessment of utilizing the Alcatraz monitoring site as a proxy to flux from other sources through the Gate in the future.

With respect to the second issue regarding representation of freshwater exchange, it is pointed out that details of the flow dynamics are not necessary but rather, the gross behavior and overall net volumetric water flux per tide cycle is required (sediment is assumed to be represented by measured SSC and calibration constants). Gravitational circulation and baroclinic flows, which become increasingly important with higher freshwater loadings, were not fully accounted for in this study as freshwater inputs were minimal and the model was implemented in a vertically averaged mode. Parameterization of changes in the flow dynamics and net flux rates could be developed with a 3D numerical model and high freshwater point source loadings. With the current state of knowledge, it is uncertain if such parameterization would result in the necessity to adjust Eq. (2).

We estimate that the mean suspended-sediment outflow from San Francisco Bay during WY2004–2010 was 1.2 Mt/yr which is less than a previous estimate of 5.0 Mt/yr during 1955–1990 developed from bathymetric surveys and conservation of mass (Schoellhamer et al., 2005). This early estimate is larger likely because it included bed load, higher freshwater flows than experienced in WY2004–2010, and it was for a period prior to a 36% step decrease in Bay SSC in 1999 that may indicate that the Bay crossed a threshold from transport to supply regulation of sediment transport (Schoellhamer, 2011).

Watershed disturbances increased sediment supply to San Francisco Bay in the 19th and early 20th centuries and since then the Bay has been geomorphically adjusting to a decreasing sediment supply (Schoellhamer et al., 2013-this issue). Schoellhamer et al. (2013-this issue) hypothesize that San Francisco Bay is still capable of adjusting but further adjustment will occur only during greater floods than previously experienced during the adjustment period. Periods of equilibrium are likely between these adjustment floods. The mean sediment outflow from San Francisco Bay during WY2004–2010 was 1.2 Mt/yr which is similar to the mean sediment inflow of 1.4 ± 0.5 Mt/yr for the same period reported by McKee et al. (2013-this issue, Table 5). Thus, during the study period, San Francisco Bay sediment inflow and outflow were roughly in balance.

Table 5
Tidal constituent amplitudes and phases for estimation of currents at the Alcatraz monitoring site.

Tidal constituent	Frequency (h^{-1})	East-directed amplitude	East-directed phase	North-directed amplitude	North-directed phase
M2	0.0805	0.49	142.94	0.26	321.14
S2	0.0833	0.14	148.19	0.07	329.77
N2	0.0790	0.11	125.19	0.06	308.28
K1	0.0418	0.11	140.88	0.06	322.51
O1	0.0387	0.08	135.68	0.05	321.70
Q1	0.0372	0.02	134.97	0.01	315.90

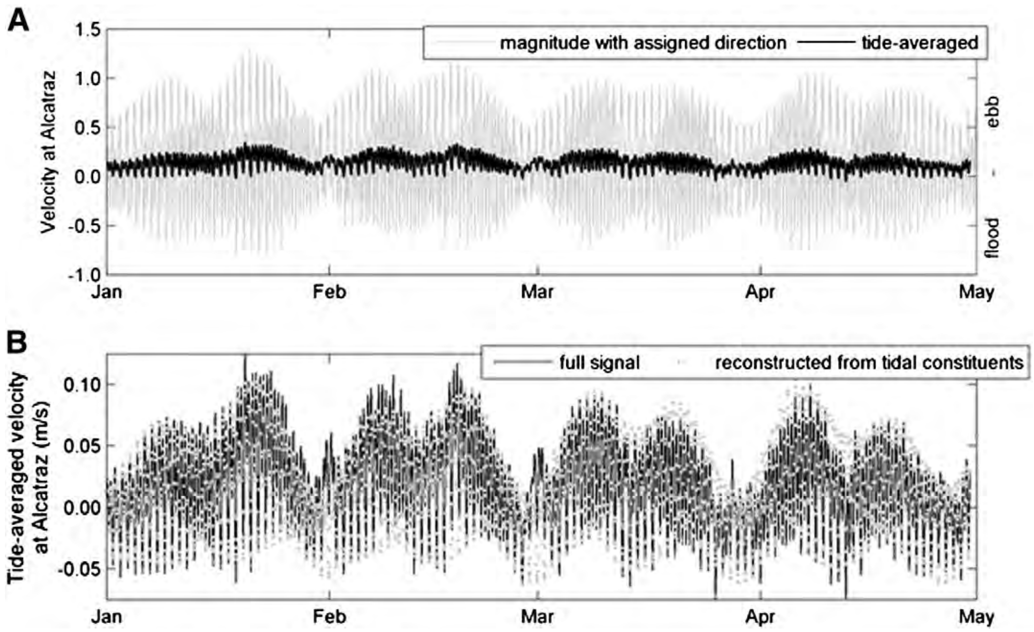

Fig. 16. Currents at the Alcatraz monitoring site. (A) Current magnitudes with assigned negative values for flood directed flows (based on tidal ellipse in Fig. 15A) and the 25 h low-pass filtered signal. (B) Comparison of the low-pass filtered time-series from the full current signal in (A) and the tide-averaged signal of currents reconstructed with tidal constituents in Table 5.

Table 6
Coefficients of determination (r^2) of advective and dispersive sediment flux terms with total flux at the Golden Gate using different tide-averaging periods.

Term	20 h tide avg.	25 h tide avg.	30 h tide avg.	35 h tide avg.
Advective	0.83	**0.86**	0.78	0.52
Dispersive	NS	0.00	0.00	0.04

NS: not statistically significant (p-value > 0.05). Bold value indicates highest value obtained.

No large floods occurred during the study period, so this result is consistent with the adjustment hypothesis.

6. Conclusions

In an effort to reduce the uncertainty of the least well characterized component of the San Francisco Bay sediment budget, an equation relating SSC measurements at the Alcatraz monitoring site with tide-averaged suspended sediment fluxes through the Golden Gate was developed. The relation was developed from suspended sediment flux rates computed with a numerical model; the model was calibrated against measurements obtained across the Golden Gate over a spring–neap tide cycle. Observed suspended sediment concentrations (SSC) from the Alcatraz monitoring station were then used to parameterize advective and dispersive fluxes and plotted against five months of hind-cast sediment flux rates at the Golden Gate.

Measurements and model simulations indicated horizontal spatial gradients of both water and sediment flux across the Golden Gate. Some of this can be attributed to the formation of eddies on both sides of the landmass points at the constriction of the Gate. At flood tide, two large counter-clockwise and one clockwise eddy forms landward of the Gate; at ebb tide, at least one of each clockwise and counter-clockwise eddy forms on the seaward side of the Gate. Depth-averaged suspended sediment concentrations showed variation across the channel; at ebb tide there was a decrease from south to north, while at flood tide, the concentrations were about equal along the channel banks and lower in the center of the channel. The rather complex flow and transport patterns observed in the measurements and elucidated with the model illustrate the added value of

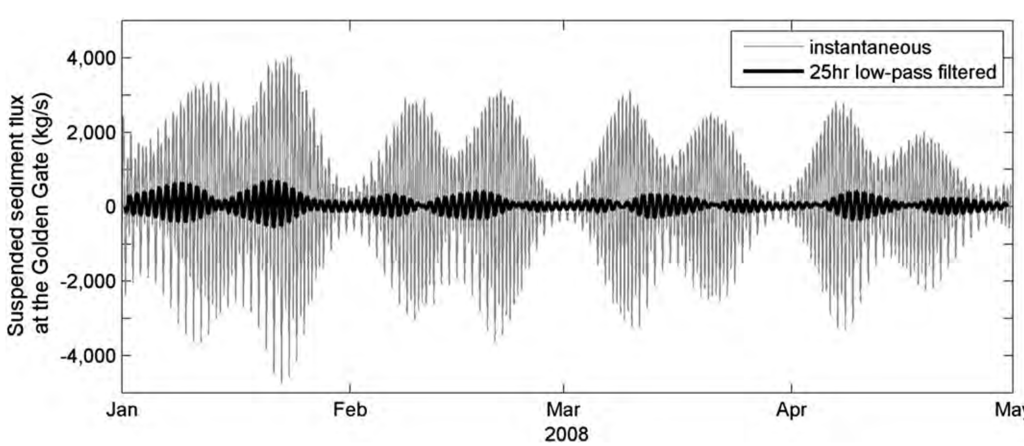

Fig. 17. Modeled suspended sediment flux across the inner transect of the Golden Gate from January through April 2008. 25 h low-pass filtered (tide-averaged) values are shown with bold line and plotted against the right axis. Positive values indicate seaward flux.

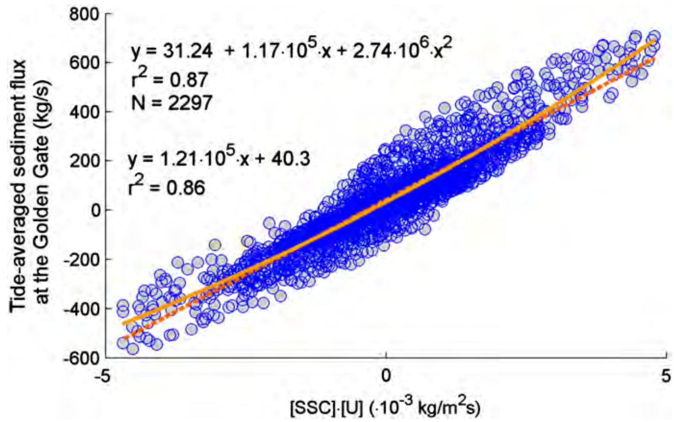

Fig. 18. Low-pass filtered (25 h) sediment flux rates at the Golden Gate versus measured SSC and computed currents at the Alcatraz monitoring site. Positive flux is seaward.

employing a numerical model to capture the net sediment flux at this site.

Suspended sediment concentrations measured at the Alcatraz monitoring station were shown to be modulated by tides and sediment loading from the Sacramento–San Joaquin Delta. Maximum tidal currents coincided with the latter part of the lower low ebb cycle at the Alcatraz monitoring site and were largely responsible for the higher SSC concentrations. The study period encompassed a critically dry water year and as a result, sediment loading rates from the Delta were unusually low. Although only weak correlations between observed SSCs at Alcatraz and model simulated flux through the Golden Gate with Delta loading rates were attained, both model simulation results and measurements indicated a sediment pulse transport rate of 8 to 12 days from Suisun to Central Bay.

A linear fit relating the 25 h tide averaged product of computed currents and observed SSCs at Alcatraz with net sediment flux through the Golden Gate was developed. Utilization of the equation with all available Alcatraz SSC data resulted in a mean sediment outflow for WY2004–2010 of 1.2 Mt/yr. This value is roughly equivalent to independently calculated sediment inflow during the study period (1.4 Mt ± 0.5, McKee et al., 2013-this issue). While there was little variation in sediment outflow from year to year, exports were computed to be greatest during the wettest water year (WY2006) analyzed but only marginally so.

Acknowledgments

We extend our gratitude to Megan Sheridan and Chris Halle at Bodega Marine Lab, Bodega, CA who collected and post-processed a significant portion of the data and Paul Buchanan who manually collected the point suspended-sediment samples used for instrument calibration. Thanks also to two anonymous reviewers who provided constructive critiques of the manuscript. Financial support was provided by the USGS San Francisco Bay project (Principal Investigator Patrick Barnard).

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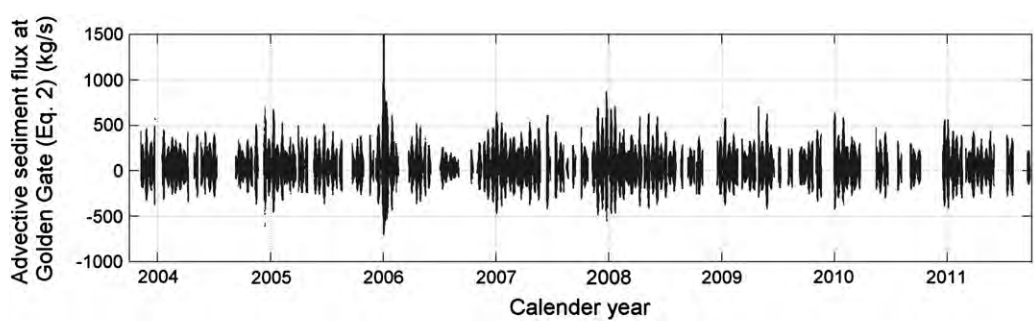

Fig. 19. Net tide averaged advective sediment flux at the Golden Gate calculated with the empirical fit, Eq. (2). Positive flux is directed seaward.

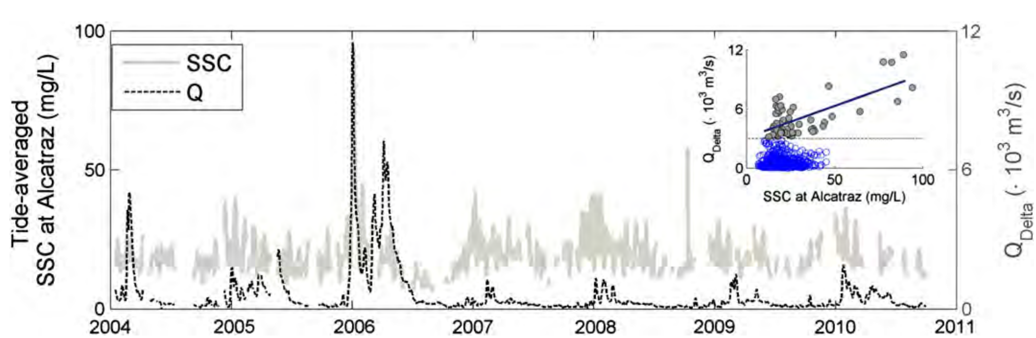

Fig. 20. Tide-averaged (30 h) SSC at Alcatraz and Delta inflows to the Bay. Inset shows the same data as a scatter plot with a least-squares linear regression ($r^2 = 0.42$) through data above a threshold of $Q_{Delta} = 3000$ m^3/s.

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Exhibit G

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Distribution of biologic, anthropogenic, and volcanic constituents as a proxy for sediment transport in the San Francisco Bay Coastal System

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ABSTRACT

Although conventional sediment parameters (mean grain size, sorting, and skewness) and provenance have typically been used to infer sediment transport pathways, most freshwater, brackish, and marine environments are also characterized by abundant sediment constituents of biological, and possibly anthropogenic and volcanic, origin that can provide additional insight into local sedimentary processes. The biota will be spatially distributed according to its response to environmental parameters such as water temperature, salinity, dissolved oxygen, organic carbon content, grain size, and intensity of currents and tidal flow, whereas the presence of anthropogenic and volcanic constituents will reflect proximity to source areas and whether they are fluvially- or aerially-transported. Because each of these constituents have a unique environmental signature, they are a more precise proxy for that source area than the conventional sedimentary process indicators.
This San Francisco Bay Coastal System study demonstrates that by applying a multi-proxy approach, the primary sites of sediment transport can be identified. Many of these sites are far from where the constituents originated, showing that sediment transport is widespread in the region. Although not often used, identifying and interpreting the distribution of naturally-occurring and allochthonous biologic, anthropogenic, and volcanic sediment constituents is a powerful tool to aid in the investigation of sediment transport pathways in other coastal systems.

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1. Introduction

With a population now exceeding seven million people, the San Francisco Bay area's economy is one of the largest in the world (Forbes, 2013). The region's financial health is dependent upon access to the major population, commerce, and recreation centers. Whether these include commercial shipping lanes, recreational watercourses, or tidal wetlands, the estuary is the primary gateway to them all. For more than a century, these waterways have been subjected to human modification by means of influx of hydraulic mining debris, infilling of tidelands to create habitable land, wetland restoration, and dredging and lowering the tops of bedrock knobs to facilitate ship traffic (Chin et al., 2004), to name a few. Because San Francisco Bay influences so many aspects of life in the area, these waterways must be maintained and understanding the regional sediment dynamics is key to this process.

Although the distribution of sediments is typically discussed in terms of sediment grain size, composition, and provenance, nothing has been previously reported on the distribution of the biological, anthropogenic, and volcanic constituents associated with the sediment. Each element provides unique information about the freshwater, estuarine, and/or marine environment in which they naturally occur. By identifying these constituents, and especially those that are allochthonous, this multi-proxy approach provides another method by which to discern patterns of sediment transport and deposition in San Francisco Bay and the nearby offshore realm.

2. Setting

San Francisco Bay consists of three subembayments—North Bay (San Pablo and Suisun Bays, including the shallow embayments referred to as Grizzly and Honker Bays), Central Bay (including Richardson Bay), and South Bay (Fig. 1A) (Chin et al., 2004). The estuary is the largest on the west coast of the United States, ranking second only to Chesapeake Bay as the largest in the United States in terms of surface area (1240 km^2; Conomos et al., 1985). It is a structural trough that formed during the late Cenozoic when the ancestral San Joaquin and Sacramento Rivers, and Coyote Creek formed a drainage basin parallel to a coastline west of the present Golden Gate Bridge (Lawson, 1894, 1914; Atwater et al., 1977; Atwater, 1979). At least four estuaries were created during the Pleistocene and Holocene (Sloan, 1992; McGann et al., 2002) as a result of a cyclical pattern of rising seawater inundating the region during interglacials and an ensuing drop in sea level during glaciation, as well

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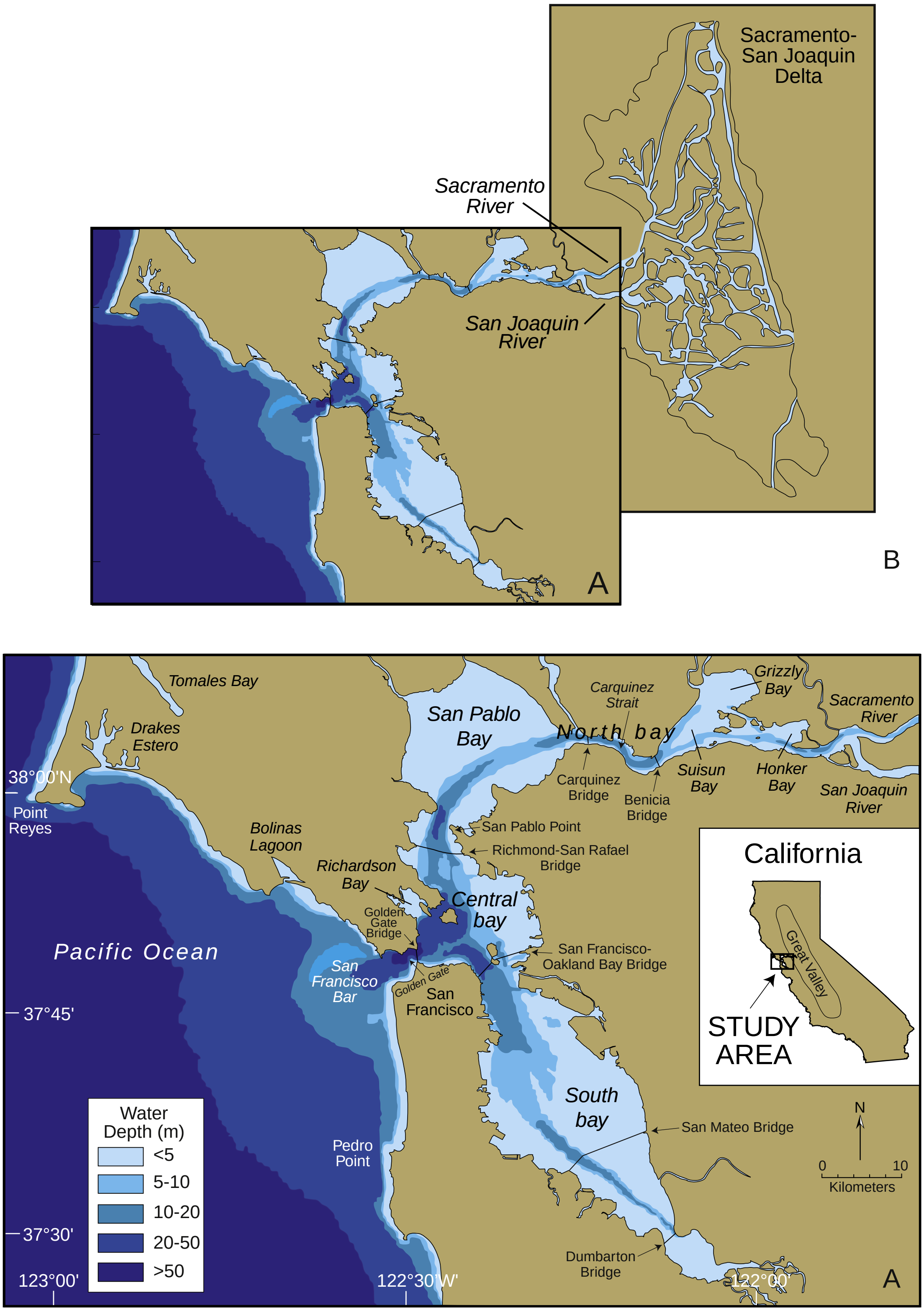


Fig. 1. A. Location map and water depth (in meters) of the San Francisco Bay Coastal System, including the offshore region and the three subembayments of San Francisco Bay: North Bay (including San Pablo, Suisun, Grizzly, and Honker Bays), Central Bay (including Richardson Bay), and South Bay. San Francisco Bar is an informal name for Potato Patch Shoal. Inset of the state of California includes the location of the Great Valley. B. Location of the Sacramento–San Joaquin Delta in relation to the San Francisco Bay Coastal System.

as tectonic subsidence between the San Andreas Fault to the west and the Hayward Fault to the east (Atwater et al., 1977). These four estuaries have been dated as early to middle Pleistocene based on the presence of the Rockland Ash (600–570 ka; Lanphere et al., 2004), an overlying Pleistocene deposit the age of which has not been precisely determined (Sloan, 1992; McGann et al., 2002), late Pleistocene (~125–120 ka; Sloan, 1992; McGann et al., 2002), and late Pleistocene to Holocene (11–10 ka; Gilbert, 1917; Louderback, 1941, 1951; Atwater et al., 1977; McGann et al., 2002). As a consequence of this last transgression, the modern estuary was established by 7.7 ka (Schweikhardt et al., 2010), the Delta marshes by ~6.6 ka (Drexler et al., 2009), South Bay by ~6 ka (Atwater et al., 1977), Central and San Pablo Bays by ~5 ka (Atwater, 1979), and tidal salt marshes by 4.7 ka (Goman et al., 2008).

San Francisco Bay is generally quite shallow, averaging only 6 m water depth (Conomos, 1979; Conomos et al., 1985; Fig. 1A). Suisun, San Pablo, and South Bays have an average depth of only 3 to 4 m, with deep tidal channels reaching 9 to 20 m. Central Bay averages 11 m water depth, and has the largest water volume of the estuary, yet only half the surface area of South Bay (The Bay Institute, 1998; Chin et al., 2004). Due to strong tidal currents which flow through the Golden Gate and carry away finer sediments (Fig. 2), this portion of the estuary is characterized by the coarsest sediment, (Fig. 3; Rubin and McCulloch, 1979). Also present are a number of submerged rock knobs that have at times posed a hazard to shipping, including Anita, Blossom, Harding, Shag, and Arch Rocks (Chin et al., 2004). The deepest part of the estuary lies in western Central Bay, reaching a maximum depth of 113 m in the vicinity of the Golden Gate Bridge (Hanes and Barnard, 2007).

The Sacramento and San Joaquin Rivers enter the estuary in the northeast from the Sacramento-San Joaquin Delta (Fig. 1B; Conomos et al., 1985) and drain 40% of the State of California, a 150,000 km^2 area. Combined, they have an average annual inflow of 600 m^{3}s^{-1}, although this fluctuates by a factor of 100 depending on seasonal precipitation (Cloern and Nichols, 1985; Conomos et al., 1985; Cloern, 1996). Although this annual inflow is significant, it is greatly reduced compared to that of 100 yrs ago as a result of changes in water management driven by growth of modern agriculture in the Great Valley (Nichols et al., 1986).

Because of the Mediterranean-type climate in central California, with rainy winters and dry summers, salinity in San Francisco Bay

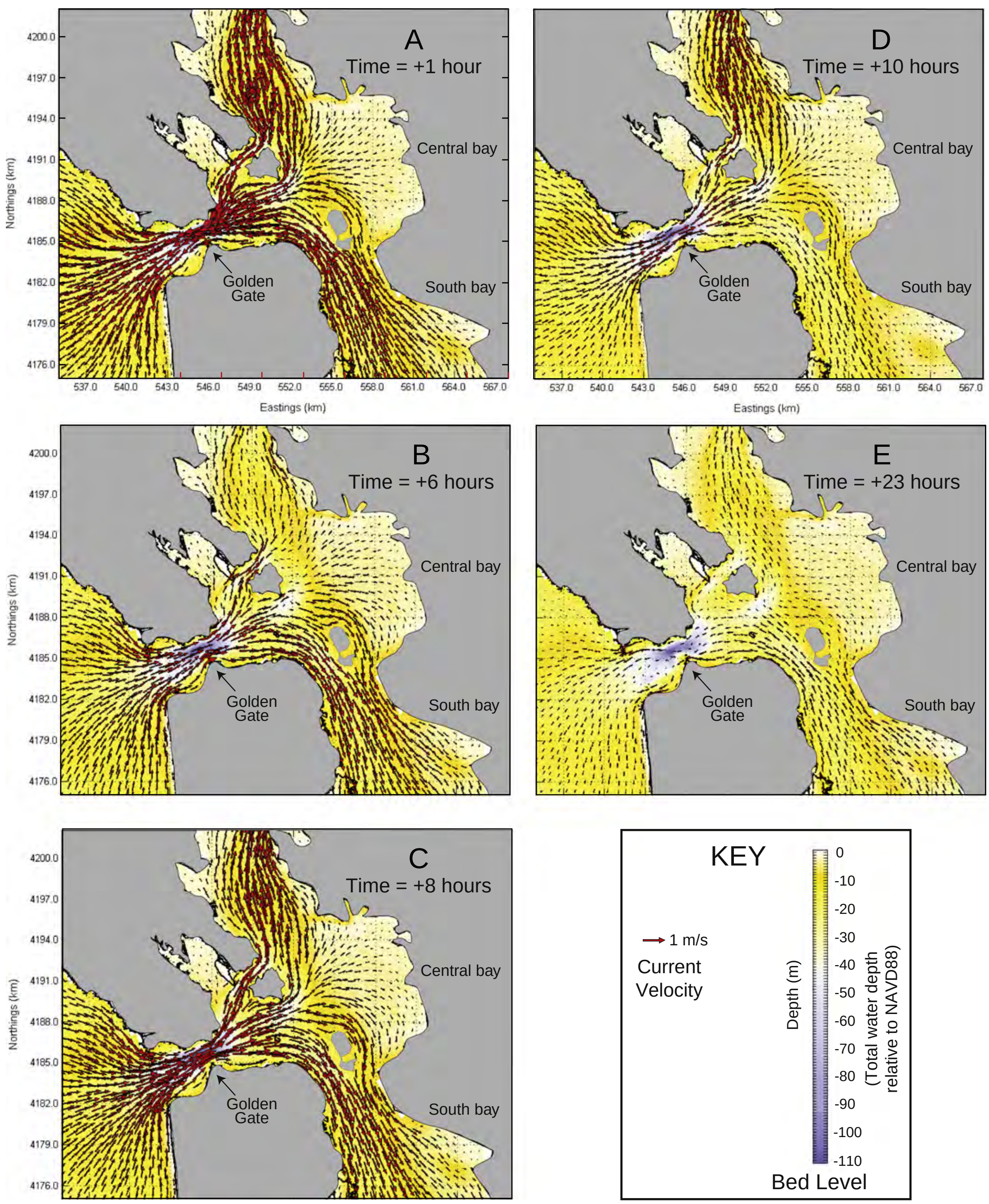


Fig. 2. Time series of tidal currents flowing between the open ocean off central California and two of the three embayments (Central and South Bays) of San Francisco Bay. Total water depth (bed level) relative to NAVD88 in meters. A. Maximum outgoing tidal stream (low tide). B. Incoming tidal stream (flood tide). C. Maximum incoming tidal stream (high tide). D. Outgoing tidal stream (ebb tide). E. Tidal stream ceases (slack tide). Figure modified from Barnard et al. (2007).

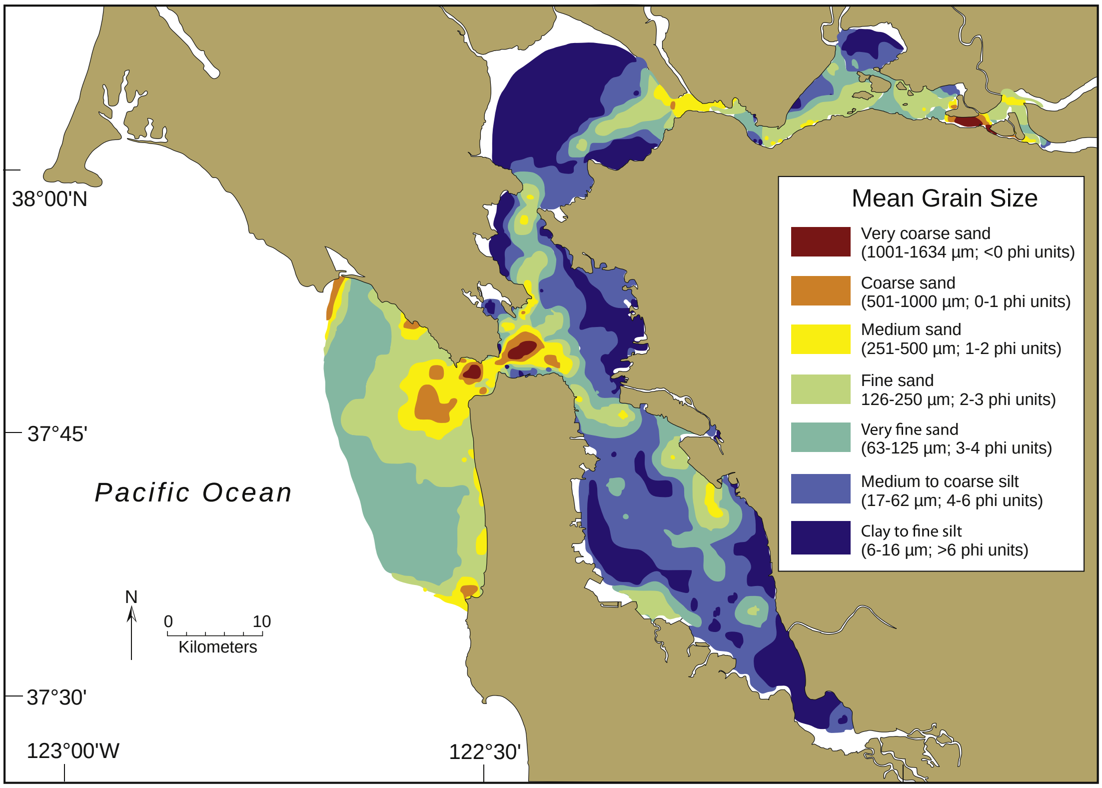


Fig. 3. Interpolated mean grain size of surface sediment samples in the San Francisco Bay Coastal System.

changes seasonally and is dependent more on river inflow than oceanic influences (Conomos et al., 1985). Salinity values of the estuarine water falls somewhere between the two end members of water from the coastal Pacific Ocean in which salinity varies little (~33–35 psu) and the Sacramento–San Joaquin Delta where freshwater prevails (~0 psu) (Fig. 4; Appendix 1; Ingram et al., 1996; San Francisco Estuary Institute, 1997, 1999, 2000). When the salinity differences are extreme, mixing of the oceanic and riverine water is substantially reduced. Estuarine temperatures also fluctuate substantially. From August 1995 to February 1998, for example, temperatures ranged between approximately 12 °C and 23 °C in the winter and summer near the confluence of the Sacramento and San Joaquin Rivers, between 9 °C and 18 °C in Central Bay, and 11 °C and 23 °C in South Bay (Fig. 5; Appendix 1; San Francisco Estuary Institute, 1997, 1999, 2000). In 2010, the temperature ranges were simliar (9 °C and 20 °C, 11 °C to 16 °C, and 11 °C to 20 °C, respectively; U.S. Geological Survey Water Resources Division San Francisco Bay Water Quality, 2012). In contrast, sea surface temperatures in the oceanic realm off San Francisco Bay are fairly constant (~13–14 °C; Mendelssohn and Schwing, 2002). As a result, winter temperatures in the Bay are cooler than the Pacific Ocean and summer temperatures are warmer. In the summer, mixing of warmer Delta or South Bay water with colder water in Central Bay may sometimes develop a sharp thermocline, suggesting slow horizontal mixing.

Because of its geographic configuration, as well as the input of riverine water in the northeast and oceanic water from the west, San Francisco Bay consists of two hydrologically distinct regimes (North Bay and South Bay) that coincide with the geographic regions (Conomos, 1979). Both the Suisun Bay and San Pablo Bay portions of North Bay (Fig. 1A) are considered partially mixed bodies of water. Suisun Bay is the most riverine influenced because of its proximity to the Sacramento and San Joaquin Rivers; San Pablo Bay lies closer to the Pacific Ocean and is influenced by both riverine and oceanic sources. During periods of abundant freshwater input into this system, the boundary between freshwater and seawater (i.e., the 2 psu line), which normally lies somewhere from the Delta to Suisun Bay (Fig. 4A–C, E), may shift substantially oceanward and be found in San Pablo Bay instead (Fig. 4D, F; http://sfbay.wr.usgs.gov/access/wqdata/index.html), causing severe stress on the existing biota (Nichols, 1985).

South Bay is a partially enclosed, tidal lagoon-type estuary (Conomos, 1979). Originally, it was thought that water circulation in this part of the Bay was sluggish compared to North and Central Bays (Conomos, 1979) yet tidal currents commonly exceed 1 m/s in the channel and 0.4 m/s in the shallow regions (Schoellhamer, 1996). It has been demonstrated that South Bay is also greatly affected by both coastal and riverine input (McCulloch, 1972; Imberger et al., 1977; Cheng et al., 1993; Knowles et al., 1997; Schemel, 1998). Changes in the salinity of South Bay due to delta outflow and input from local rivers, not tidal flushing, occur during periods of high delta and river discharge, but also during normal and less than normal winter flows. In fact, the effects of delta inflow are considered more of a controlling factor on salinity than local inflow as far south as the San Mateo Bridge, with delta inflow reaching as far south as the Dumbarton Bridge (Peterson et al., 1995). As a result, in the winter and spring, increased precipitation and inflow results in decreased salinity values in South Bay (Fig. 4B, D, and F), whereas in the summer, the salinity reaches nearly oceanic values (Fig. 4A, C, and E) due to a lack of precipitation, decreased riverine inflow, and increased evaporation. Throughout both North and South Bays, wind and tides are also important factors in that they influence water column mixing and stratification, as well as water turbidity (Cloern and Nichols, 1985; Cloern, 1996), thereby affecting primary productivity and, ultimately, benthic macro- and microfaunas.

Central Bay lies geographically between North and South Bays and is closest to the Pacific Ocean, exchanging water with the marine realm through a narrow inlet known as the Golden Gate. As a result, Central Bay is the region in the estuary most influenced by the ocean. Currents flowing through this inlet can exceed 2.5 m/s (Barnard et al., 2007). Ebb flows through the Golden Gate decrease quickly in velocity, resulting in the deposition of coarse sediment (Fig. 3). This sediment, as well as some contributed by the littoral drift, form a massive ebb-tidal delta seaward of the Bay known as Potato Patch Shoal that is informally referred to as the

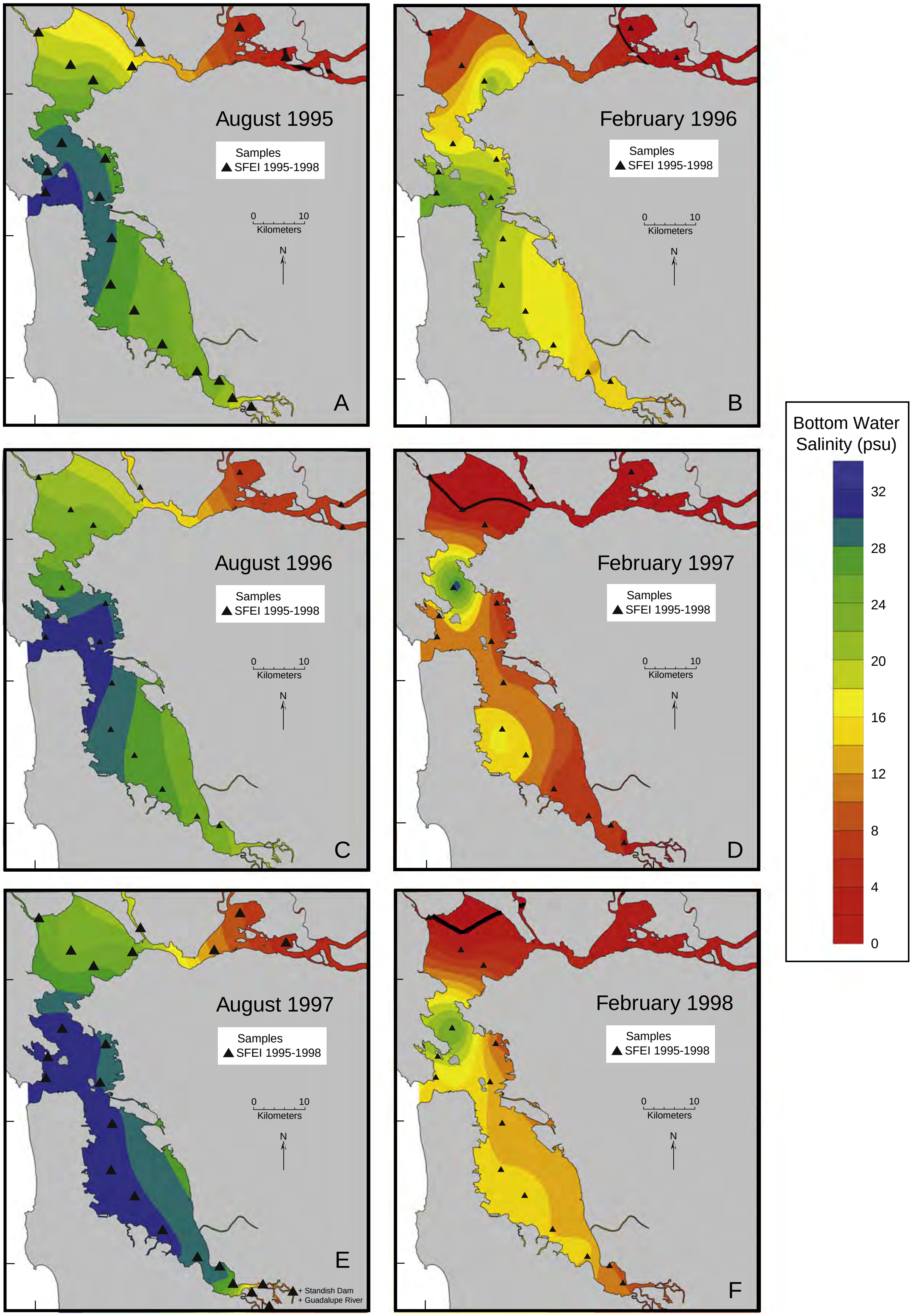


Fig. 4. Interpolated bottom water salinity (psu) for San Francisco Bay based on the San Francisco Estuary Institute samples collected between August 1995 and February 1998. The boundary between freshwater and seawater (the 2 psu line), if present, is shown as a heavy black line.

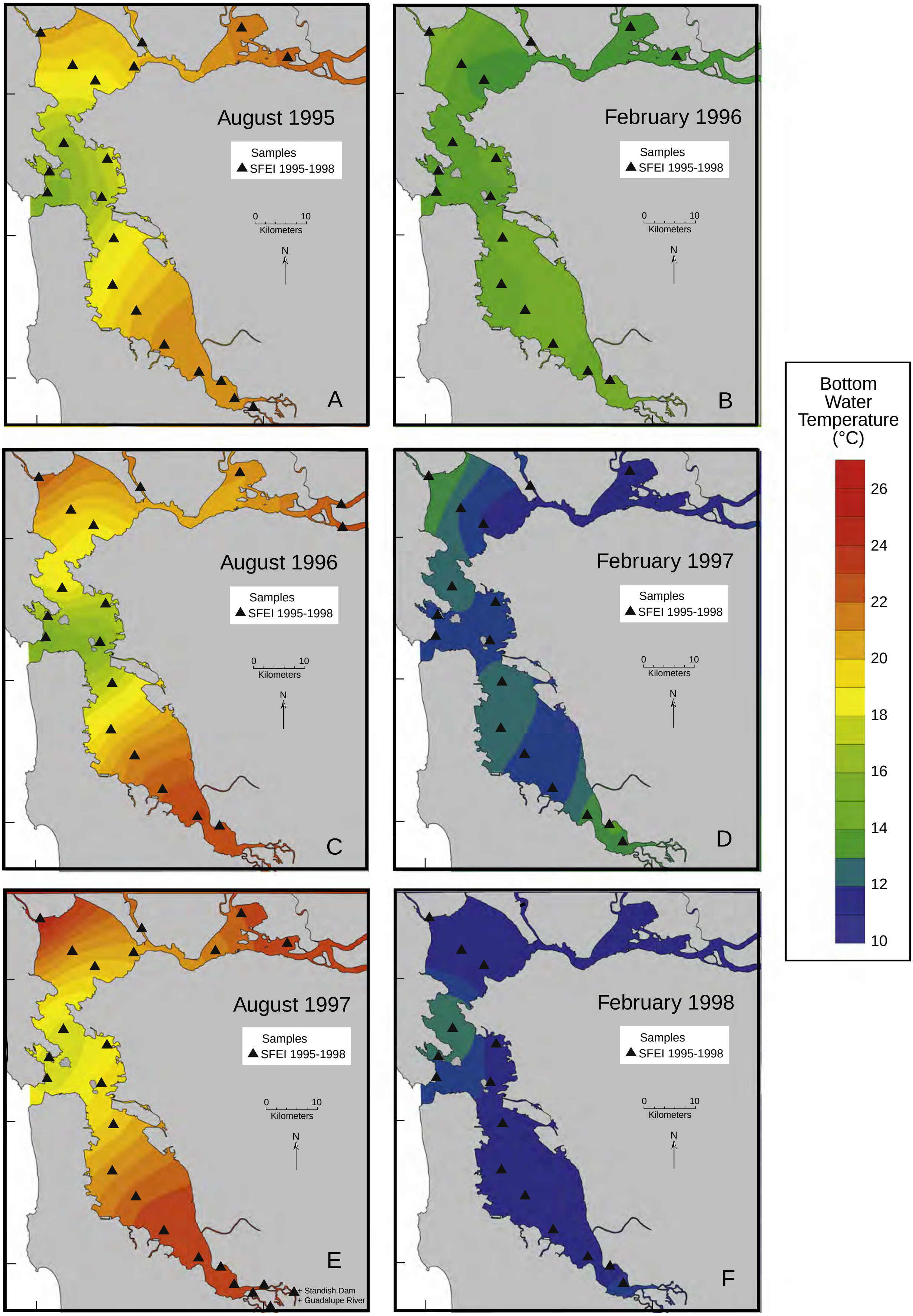


Fig. 5. Interpolated bottom water temperature (°C) for San Francisco Bay based on the San Francisco Estuary Institute samples collected between August 1995 and February 1998.

San Francisco Bar in this study. The bar covers a region of approximately 100–175 km^2, with an average depth of 17 m (Hanes and Barnard, 2007; Dallas and Barnard, 2009; Barnard et al., 2013-in this issue-b).

3. Previous work

Detailed studies of the biota of the San Francisco Bay region began in the early 1900s. Samples acquired by the U.S. Steamer *Albatross* in 1912–1913 were used to investigate the molluskan fauna in the Bay (Packard, 1918a, 1918b), describing the species and environmental factors affecting their distribution. Shortly thereafter, Hanna and Church (1927) described the benthic foraminifera in one sample obtained between the Farallon Islands and Point Reyes, and McDonald and Diediker (1930) investigated the distribution of foraminifera from the newly erected (1927) Dumbarton Bridge in South Bay to Suisun Bay in the north, as well as two additional stations along the coast. Schenck (1940) reported on the distribution of two foraminiferal species from the estuary and the adjacent littoral zone of the open-ocean coast, and Bandy (1953) discussed the benthic foraminiferal fauna in scattered samples off San Francisco from the beach to the lower slope. Nearly a half-century later, detailed distributional studies were undertaken in San Francisco Bay: Slater (1965) in Suisun Bay, Means (1965) in Richardson Bay, Quinterno (1968) and Arnal et al. (1980) in South Bay, Locke (1971) in San Pablo Bay, Connor (1975) in the shallow northern regions of Richardson Bay, Wagner (1978) in the northern portion of South Bay, Central Bay, near the Carquinez Strait, and outside the Golden Gate, and Sloan (unpublished data from 1980 to 1981) in North, Central, and South Bays. Hedman (1975) published on recent and fossil foraminifera from Bolinas Lagoon. A decade later, the distribution of diatoms in surface samples of San Francisco Bay was described by Laws (1988).

Atwater et al. (1977) was the first publication on San Francisco Bay to utilize not only foraminifera, but a range of micro- and macroscopic plant and animal fossils, including ostracods, diatoms, and seeds, to understand the depositional and environmental history of late Quaternary sediments. From borehole samples, they dated Holocene sea levels, documented sea-level fluctuations, and measured vertical crustal movement. Sloan (1980, 1992) followed with a similar study using multiple sand-sized organic constituents, among them foraminifers, diatoms, ostracods, molluscan shells, fish elements, radiolarians, and plant fragments and seeds, from boreholes drilled for the proposed "Southern Crossing" in South Bay to investigate the depositional history and paleoenvironment of the youngest Pleistocene estuary (i.e., the informally named "Yerba Buena mud member of the San Antonio Formation"; Sloan, 1992). Other borehole studies in the estuary that used both sedimentologic and biologic constituents include those of Ross (1977), Wagner (1978), and Atwater et al. (1981). Microbiota have also been used since the 1990s to investigate paleoclimate and climate change, as well as the impact of pollution and invasive species, in San Francisco Bay (e.g., Ingram and DePaolo, 1993; McGann, 1995, 2008; Ingram et al., 1996; McGann et al., 2000; Starratt, 2004; Lesen, 2005; Schweikhardt et al., 2010; Lesen and Lipps, 2011). To our knowledge, this present study is the first to use biologic, anthropogenic, and volcanic sediment constituents to provide information on recent sediment transport in the San Francisco Bay Coastal System.

In addition to the early faunal investigations in San Francisco Bay, samples acquired by the U.S. Steamer *Albatross* in 1912–1913 were also used to construct a map of bottom sediment texture throughout the Bay (Sumner et al., 1914). Shortly thereafter, Gilbert (1917) investigated the impact of sediment discharged into the Bay due to large-scale hydraulic gold-mining in the Sierra from 1852 to 1884. Later investigations and estimates of net sediment deposition from this activity were presented by Krone (1979), Porterfield (1980), Meade (1982), Capiella et al. (1999), Foxgrover et al. (2004), Jaffe et al. (2007), and Fregoso et al. (2008).

The enormous input of sediment into San Francisco Bay in the late 1880s was followed by a drastic reduction after 1910 due to the construction of dams, reservoirs, stream diversions, and withdrawal of water for agriculture (Knowles and Cayan, 2004; Wright and Schoellhamer, 2004; Ganju et al., 2008). Aggregate mining, dredging, and borrow pit mining has also been responsible for the removal of large quantities of sediment from the Bay (Scheffauer, 1954; United States Army Corps of Engineers, 1975; Chin et al., 2004; Dallas, 2009; Dallas and Barnard, 2009, 2011). These studies have lead to estimates on overall sediment loss trends within the Bay and nearby offshore area (Capiella et al., 1999; Foxgrover et al., 2004; Jaffe and Foxgrover, 2006; Hanes and Barnard, 2007; Jaffe et al., 2007; Fregoso et al., 2008; Barnard and Kvitek, 2010; Dallas and Barnard, 2011; Schoellhamer, 2011). Further studies highlighting the physical processes, and resulting sediment pathways and geomorphology in the San Francisco Bay Coastal System are presented in this special issue.

4. Methods

Bulk sediment samples for microfaunal and sedimentological analysis were collected by the San Francisco Estuary Institute (SFEI) onboard the *RV David Johnston* at 26 stations throughout San Francisco Bay twice a year during the dry- (August) and wet- (February) seasons between 1995 and 1998 (Figs. 6, 7; Appendix 1). Sediment was obtained by subsampling the upper 2.5 cm of two successive Van Veen grabs so that approximately 200 cm^3 was recovered at each site. In the laboratory, 106 of these sediment samples were wet-sieved through nested 1.0 mm, 0.150 mm, and 0.063 mm screens to segregate the size fractions and remove silt and clay; none were stained prior to washing to determine if any specimens were alive when collected. Sediment remaining on the screens was transferred to filter paper and air-dried. Due to time constraints, foraminifera were only extracted from the coarser fraction (≥0.150 mm) and the <0.150 mm fraction was archived. Each sample was split with the aid of a microsplitter into an aliquot containing at least 300 benthic foraminifers, and all specimens were picked and identified from this aliquot. If the sample contained <300 foraminifers, all that were present were picked. Samples with very fine sand to coarse sand containing few foraminifers were floated in sodium polytungstate at a specific gravity of 2.42 in order to concentrate the foraminifers before picking.

On January 8–23, 1998, the U.S. Geological Survey (USGS) again used the *RV David Johnston* (USGS CMG cruise J-1-98-SF; http://walrus.wr.usgs.gov/infobank/) to document the nature and thickness of Quaternary sediment in Central Bay. In addition to multibeam and sidescan sonar data, they obtained 56 sediment samples with a small Van Veen grab sampler to characterize the texture of surface sediments for sediment distribution and transport studies (Fig. 7; Appendix 1). More than a decade after these samples were collected, 55 were analyzed for foraminifera and other organic and inorganic constituents in a manner similar to the 1995–1998 SFEI samples, except that the ≥0.063 mm fraction was used instead. We assume the one remaining sample (#9) was unavailable because it was used in its entirety for grain size analysis.

A Smith–MacIntyre grab sampler was used onboard the *RV Parke Snavely* of the USGS from January 23–26 and March 17–20, 2010 (USGS PCMSC cruises S-7-10-SF and S-8-10-SF, respectively) to characterize sediment grain size, composition, and provenance throughout the San Francisco Bay Coastal System. During the January cruise, 59 samples were collected off the northern shore of the city of San Francisco through Central Bay, into San Pablo Bay, and then into Suisun Bay and eastward to the confluence of the Sacramento and San Joaquin Rivers. In March, 107 samples were obtained in South Bay, again in Central Bay, through the Golden Gate, out onto the San Francisco Bar, and offshore along the coast from Point Reyes to just south of Pedro Point, Pacifica. The study area was divided into six geographic areas ("provinces") that reflect discrete hydrographic and geographic regions (Figs. 6, 7; Appendix 1) and

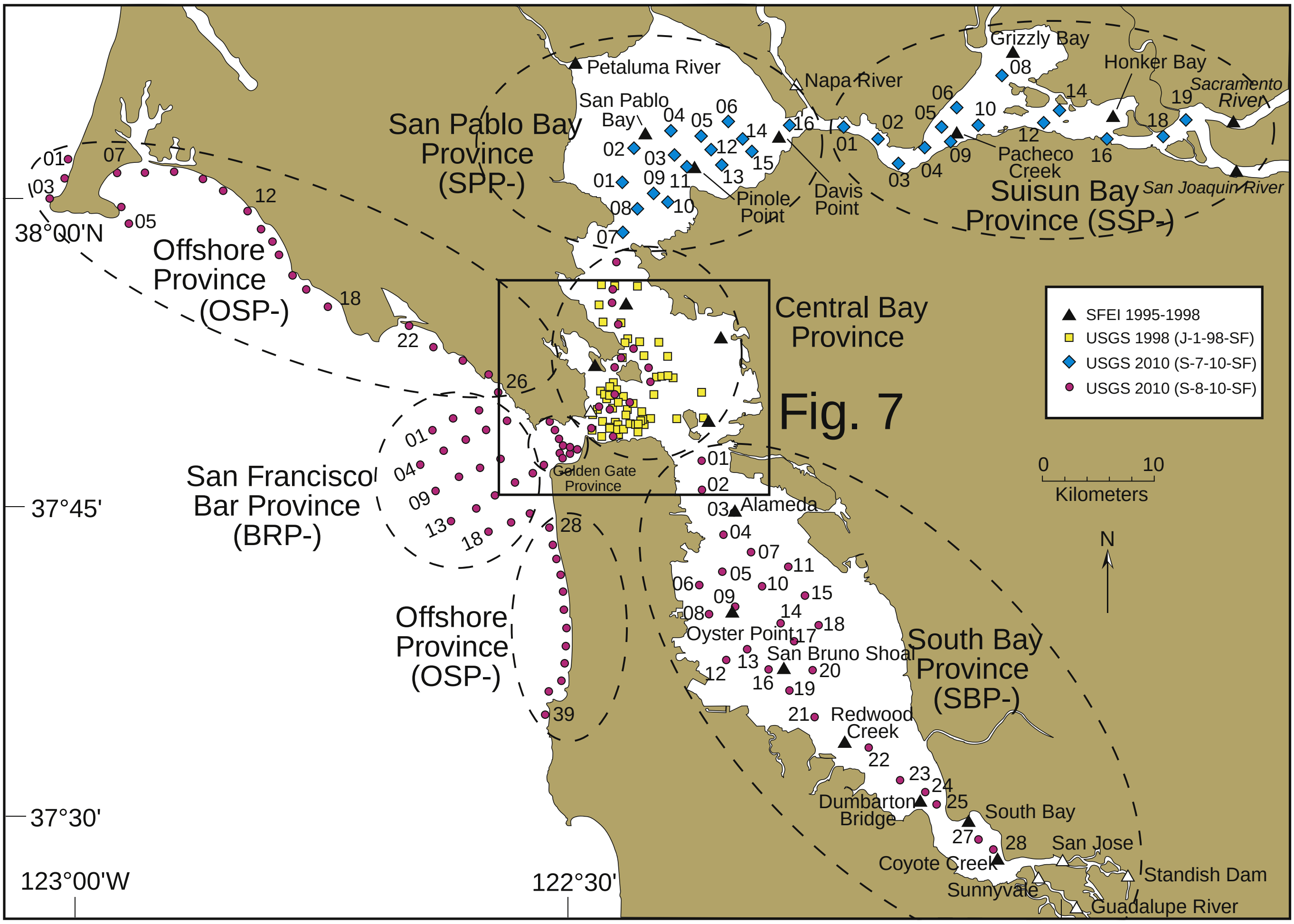


Fig. 6. Location of the stations in the San Francisco Bay Coastal System and the sand provinces. Sites includes those collected by the San Francisco Estuary Institute from 1995 to 1998, as well as those collected by the U.S. Geological Survey in 1998 (J-1-98-SF) and 2010 (S-7-10-SF and S-8-10-SF). The sand provinces are outlined in dashed lines.

the samples are named according to those regions: Suisun Bay Province (SSP), San Pablo Bay Province (SPP), Central Bay Province (CBP), South Bay Province (SBP), Golden Gate Province (GGP), San Francisco Bar Province (BRP), and Offshore Province (OSP). Approximately 200 cm^3 of the upper 2 cm of sediment was obtained at each location to investigate the organic and inorganic constituents contained therein. These samples were preserved and stained in a mixture of >70% ethanol and rose Bengal stain at a concentration of 2 g/L of ethanol (Lutze and Altenbach, 1991) for 24 h in order to recognize foraminifera that were living, or recently alive, at the time of collection (Bernhard, 1988, 2000). Fortunately, the staining proved successful despite the fact that these samples were collected in the winter when few living specimens would be expected as this is prior to the spring reproductive phase (Murray, 1983). The sediment was then wet-sieved to retain the ≥0.063 mm fraction, dried, and floated in sodium polystungstate to concentrate the organic and less dense inorganic constituents. The ≥0.063 mm fraction of the 166 samples was picked of all or a split (>300) of the foraminifera present and presence/absence (i.e., the presence or absence of each species in each sample) counts were compiled for these samples. The number of stained (i.e., living) specimens present was then tabulated among these >300 specimens.

Because different size fractions (≥0.150 mm and ≥0.063 mm) and both percentage abundances and presence/absence (P/A) data were used in the four data sets, the relative foraminiferal species abundances are not comparable. For that reason, the frequency data from the 1995 to 1998 SFEI and 1998 USGS studies were converted to P/A as was used in the two 2010 studies. Once converted, R- and Q-mode cluster analyses were utilized to describe the relationship between the benthic foraminiferal faunas, grouping the species and stations, respectively, according to their degree of similarity. As the data were already in P/A format, no transformation was necessary. Clustering was based on a Sørenson similarity coefficient and amalgamated by a group averaged linkage strategy. The Sørenson similarity coefficient was used because it is the Bray-Curtis similarity measure calculated on P/A data, the latter of which is a satisfactory coefficient for biological data on community structure because it downweights the contributions of the less common species (Clarke and Gorley, 2006). Principal Components Analysis (PCA) was performed on the 1995–1998 SFEI data as well, because it was the most complete environmental (abiotic) data set available in this study. Two analyses were performed: the abiotic factors which were normalized before analysis, and the foraminiferal (P/A) and abiotic factors combined which were 4th root-transformed to yield a more symmetric distribution and then normalized prior to analysis. Average taxonomic distinctness ($\Delta+$) and total taxonomic distinctness ($S\Delta+$) were used as biodiversity measures because they are applicable to P/A data (Clarke and Gorley, 2006), but neither provided meaningful results so a rarefaction analysis was performed instead on the frequency abundance data available for the 1998 Central Bay and 1995–1998 baywide SFEI studies. Primer v. 6.1.6, a statistical software package created by Primer-E, Ltd., was used for the cluster, PCA, and biodiversity analyses (Clarke and Gorley, 2006).

In addition to the foraminifera, a few representative specimens of the other biologic (microfauna, macrofauna, and seeds), anthropogenic

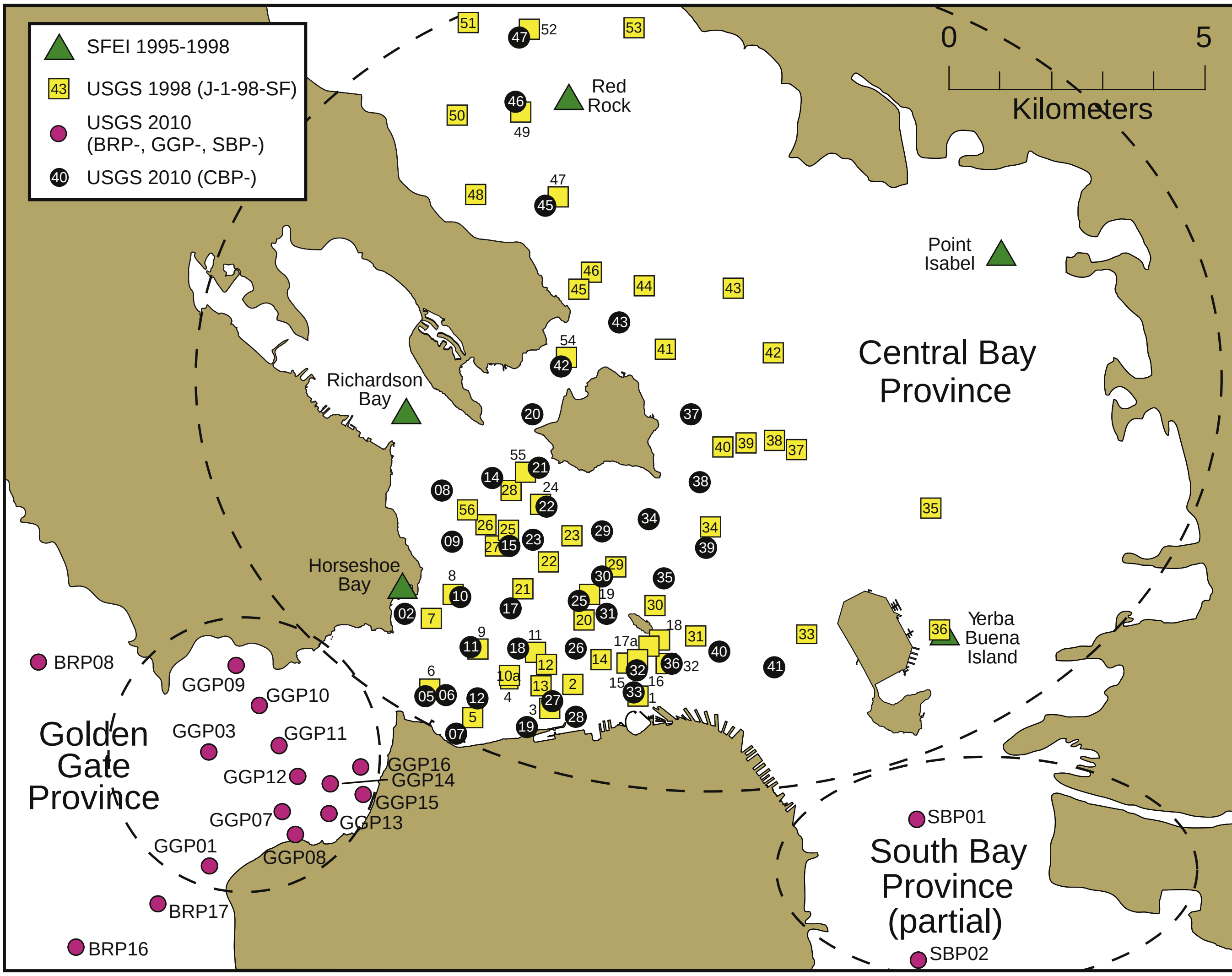


Fig. 7. Detailed map of the stations and sand provinces in Central Bay, the Golden Gate, the eastern portion of the San Francisco Bar, and the northern part of South Bay. The sand provinces are outlined in dashed lines.

(welding slag and glass microspheres), and volcanic constituents (shards of tephra) present in the sieved sediment samples were picked out, mounted on the foraminiferal assemblage slides, and identified. All of these slides and the sample residues are on file at the U.S. Geological Survey in Menlo Park, California. The seeds and ostracods were identified in part based on a reference slide collection housed at the University of California Berkeley, Department of Earth and Planetary Science (Sloan, 1980); the seeds were originally identified by the Seed Taxonomy Laboratory of the California Department of Food and Agriculture in Sacramento, California.

Disseminated tephra, in particular, isotropic volcanic glass shards, were observed in many sieved and sized (≥0.150 mm-fraction) foraminiferal residues. Between 100 and 200 volcanic glass shards were handpicked from five processed samples (SFEI August 1995 Pinole Point and Red Rock sites; 1998 Central Bay sites 3, 28, and 47) using a very fine brush dampened with water; then each grain was positioned onto the prepared surface of a labeled niche in a 10-hole electron microprobe mount custom-made by the USGS Tephrochronology Laboratory in Menlo Park, California. The mounted tephra samples were then submitted to the Tephrochronology Laboratory for petrographic description and electron microprobe analysis (EMA).

In the laboratory, the mounted volcanic glass samples were examined under plane-polarized light, a gypsum plate, and crossed nichols. The shard morphology was described, and the condition of shard types was also noted. All of the sample processing and petrographic descriptions, raw and recalculated geochemical data, and tephrochronologic interpretations are archived in the USGS Tephrochronology Project computer databases and the analyzed electron microprobe mount of volcanic glass samples is archived in the reference sample collection.

Electron microprobe analysis (EMA) of each of the five volcanic glass samples was conducted using the JEOL8900 Electron Microprobe in the USGS Electron Microprobe Laboratory in Menlo Park, California. To chemically characterize silicic glass samples, we measured the concentrations of six major oxides (silicon, aluminum, calcium, iron, potassium, and sodium) and three minor oxides (titanium, manganese, and magnesium) in 30 glass shards per sample. Iron and calcium oxides are particularly stable and useful for identifying individual tephra layers, and increased hydration is typically observed in older volcanic samples. External and internal standards, respectively GSC (Corning Glass Standard), An40 (an anorthite), and RLS-132 (a homogeneous obsidian from La Puebla, New Mexico), were used to maintain precision and accuracy. The ZAF data reduction program was used to obtain oxide concentrations. Next, the raw EMA data were averaged and normalized to 100% weight-percent oxide to account for hydration of each glass population. Afterwards, the recalculated EMA results were compared to ~6000 previously analyzed volcanic glass samples in the Tephrochronology Project geochemical database. Similarity coefficient matches of >0.95 using numerical and statistical programs such as SIMANAL and RATIONAL (described in Sarna-Wojcicki et al., 1984; Sarna-Wojcicki and Davis, 1991; Sarna-Wojcicki et al., 1997; Sarna-Wojcicki, 2000), and additional supporting criteria such as mineralogy, shard morphology, fossil, and other evidence were also evaluated to reliably identify and constrain the age of the volcanic ash, and determine its eruptive source area.

5. Results

Analysis of the 332 samples from the San Francisco Bay Coastal System yielded a diverse array of sediment constituents (Appendix 2), among them the remains of numerous species of benthic foraminifera, ostracods, diatoms, thecamoebians, arthropods (barnacles), bivalves, bryozoan, grastropods, echinoderms, worms, and seeds (see Appendix 3 for a taxonomic list), as well as glass microspheres, welding slag, and volcanic glass. A summary of the primary constituents and their spatial distribution is presented below.

5.1. Benthic foraminifera

Fifty-three species of agglutinated and calcareous benthic foraminifera were identified in 332 samples from inside San Francisco Bay and the adjacent coastal area (Appendix 4). All are found today in nearshore, shallow embayments or estuaries along the Pacific Coast of North America (Phleger, 1967; Scott et al., 1976; Ingle, 1980; Murray, 1991; Jennings and Nelson, 1992; McCormick et al., 1994; McGann, 2007). Included among these is the invasive species *Trochammina hadai*, which has now been found in 14 ports and estuaries from San Diego Bay, southern California to Prince William Sound, Alaska (McGann et al., 2000; McGann, unpublished data). Of the species recovered, the most common are *Ammonia tepida*, *Elphidiella hannai*, *Elphidium excavatum*, and *T. hadai*. Species richness ranged from 1 to 20 species/sample, with a mean of 8 species/sample. A rarefaction analysis (hypergeometric distribution for rarefaction; Hurlbert, 1971; Hayek and Buzas, 1997) revealed that at sample sizes of 10, 20, 50, 100, 200, and 300 specimens, the expected number of species present in the samples is 3.2, 4.0, 5.1, 5.9, 6.7, and 7.0, respectively. Very rare recrystallized fossil specimens were also recovered in Suisun Bay (SSP16), San Pablo Bay (SPP13), Central Bay (2, 12, 47, 52, and 54), South Bay (SFEI Standish Dam), and offshore (OSP28).

An R-mode cluster analysis using the presence/absence data of the fifty-three benthic foraminifera identified produced six taxonomic associations and 14 outliers at a Sørenson similarity coefficient of about 7 (Fig. 8). Taxonomic Association 1 (TA1) is composed of three agglutinated species, *Entzia tetrastomella* (formerly *Trochammina macrescens*; Holzmann et al., 2012), *Haplophragmoides subinvolutum*, and *Miliammina fusca*, that commonly reside in marsh to brackish shallow subtidal regions characterized by variable salinity and temperature. Taxonomic Association 2 (TA2) is a grouping of the calcareous species *Ammonia tepida*, *Elphidium excavatum*, *Elphidiella hannai*, *Haynesina germanica*, and *Elphidium gunteri*, as well as the agglutinated taxa *Trochammina hadai* and *Trochammina inflata*. These species are the most commonly encountered in San Francisco Bay and are representative of an estuarine subtidal environment. Taxonomic Association 3 (TA3) combines estuarine species (*Bolivina striatula*, *Fursenkoina pontoni*, and *Textularia earlandi*) with others that reside offshore in the marine realm (*Bulimina denudata*, *Guttulina communis*, *Fissurina* sp. A., and *Reophax* sp. A). The stations where this association is most commonly represented occur in South Bay, so TA3 is considered to be the South Bay expression of estuarine-indicating TA2 with the addition of a marine component. Taxonomic Associations 4 and 5 (TA4 and TA5) are composed of "transitional" species in that they may reside in estuarine waters bordering the open ocean or shallow marine environments. Those that were recovered in both shallow and deep estuarine waters within the Bay are assigned to TA4 and include *Buliminella elegnatissima*, *Rosalina globularis*, *Buccella frigida*, *Nonionella stella*, *Quinqueloculina bellatula*, *Elphidium magellanicum*, *Trochammina charlottensis*, *Trochammina pacifica*, and *Trochammina kelletae*. The following species were most commonly recovered in deeper estuarine waters and offshore and comprise TA5: *Bolivina vaughani*, *Eggerella advena*, *Cibicides lobatulus*, and *Spiroplectammina biformis*. Taxonomic Association 6 (TA6) is a distinct group of nine offshore taxa, the most abundant of which are *Trichohyalus ornatissima*, *Rotorbinella campanulata*, *Cibicides fletcheri*, *Buccella tenerrima*, and *Cassidulina limbata*. The remaining outliers were recovered as only rare specimens and were not significant in defining any taxonomic associations. A Q-mode cluster analysis amalgamated the 303 stations at which benthic foraminifera were recovered into four clusters and 22 outliers at a Sørenson similarity coefficient of about 32 (Fig. 9). They are referred to here as Station Clusters (SC) 1–4 and the outliers. Station Clusters 2 and 4 are further divided into subclusters 2A–D and 4E–F, respectively.

Foraminifera from 25 stations recovered at water depths of <1–9 m (averaging 5 m; Table 1) grouped to form Station Cluster 1 (SC1). These sites are located in the northern portion of the estuary in Honker, Grizzly, and Suisun Bays, in the Napa River, and in the center of San Pablo Bay. Eight additional sites are located in the middle of Central Bay from the Richmond–San Rafael Bridge to the western end of the Berkeley Pier, as well as one in Richardson Bay, and Coyote Creek, Sunnyvale, and Standish Dam at the extreme southern end of South Bay. The abundance of foraminifera is low (Benthic Foraminiferal Number [BF#] averaging 16 species/gram dry weight of sediment), species richness is low (1–7 species/sample, averaging 4), living specimens comprised 0–38% (averaging 17%) of the fauna, and the fauna is dominated by agglutinated taxa, including *Trochammina inflata*, *Haplophragmoides subinvolutum*, *Miliammina fusca*, *Trochammina hadai*, and *Entzia tetrastomella*, as well as the less abundant calcareous taxon *Ammonia tepida*.

Station Cluster 2 (SC2) encompasses the largest number of stations (142) in this study (Fig. 9). The samples were recovered from 1 to 35 m water depth, but average only 9 m (Table 1). The sites are located in the center of San Pablo Bay, at Pinole Point and Petaluma and Napa Rivers, in Central Bay at Red Rock, Point Isabel, Yerba Buena Island, Horseshoe Bay, Richardson Bay, at 22 sites on an arc east of Angel Island from Tiburon Point to San Francisco, at two locations out on the San Francisco Bar, as well as throughout South Bay down to Coyote Creek. The species richness is higher (2–20 species/sample, averaging 8) than the previous fauna, living specimens comprised 0–56% of the fauna and averaged 11%, and the foraminiferal abundance is the highest encountered in the study (BF# = 230). Calcareous taxa dominate this fauna, including *Ammonia tepida, Elphidium excavatum, Elphidiella hannai, Haynesina germanica*, and *Elphidium gunteri*. *Trochammina inflata* and the invasive species *Trochammina hadai* are also common, but the other agglutinated species (i.e., *Haplophragmoides subinvolutum*, *Miliammina fusca*, and *Entzia tetrastomella*) are far less abundant than in SC1.

Although *Ammonia tepida*, *Trochammina hadai*, and *Trochammina inflata* were recovered at nearly every station in Station Cluster 2, the cluster can still be divided into four subclusters based on the remaining faunal constituents (Fig. 9). Twelve stations scattered throughout San Francisco Bay along the periphery in regions with seasonally low salinity grouped to form subcluster SC2A. These stations are characterized by very rare *Elphidium excavatum* and *Miliammina fusca*, the absence of *Elphidiella hannai*, *Haplophragmoides subinvolutum*, and *Entzia tetrastomella*, and a predominance of clay and silt.

Twenty-six stations located primarily in Central and South Bays constitute subcluster SC2B. They differ in faunal composition compared to SC2A in that *Elphidiella hannai* occurs at each station and *Elphidium excavatum* at all but three, *Haplophragmoides subinvolutum* is no longer absent but very rare, and sand is the predominant grain size.

Subcluster SC2C is the largest with 81 stations and is situated in all parts of San Francisco Bay. This subcluster is unique in that it is dominated by all the typical estuarine species (*Ammonia tepida*, *Elphidium*

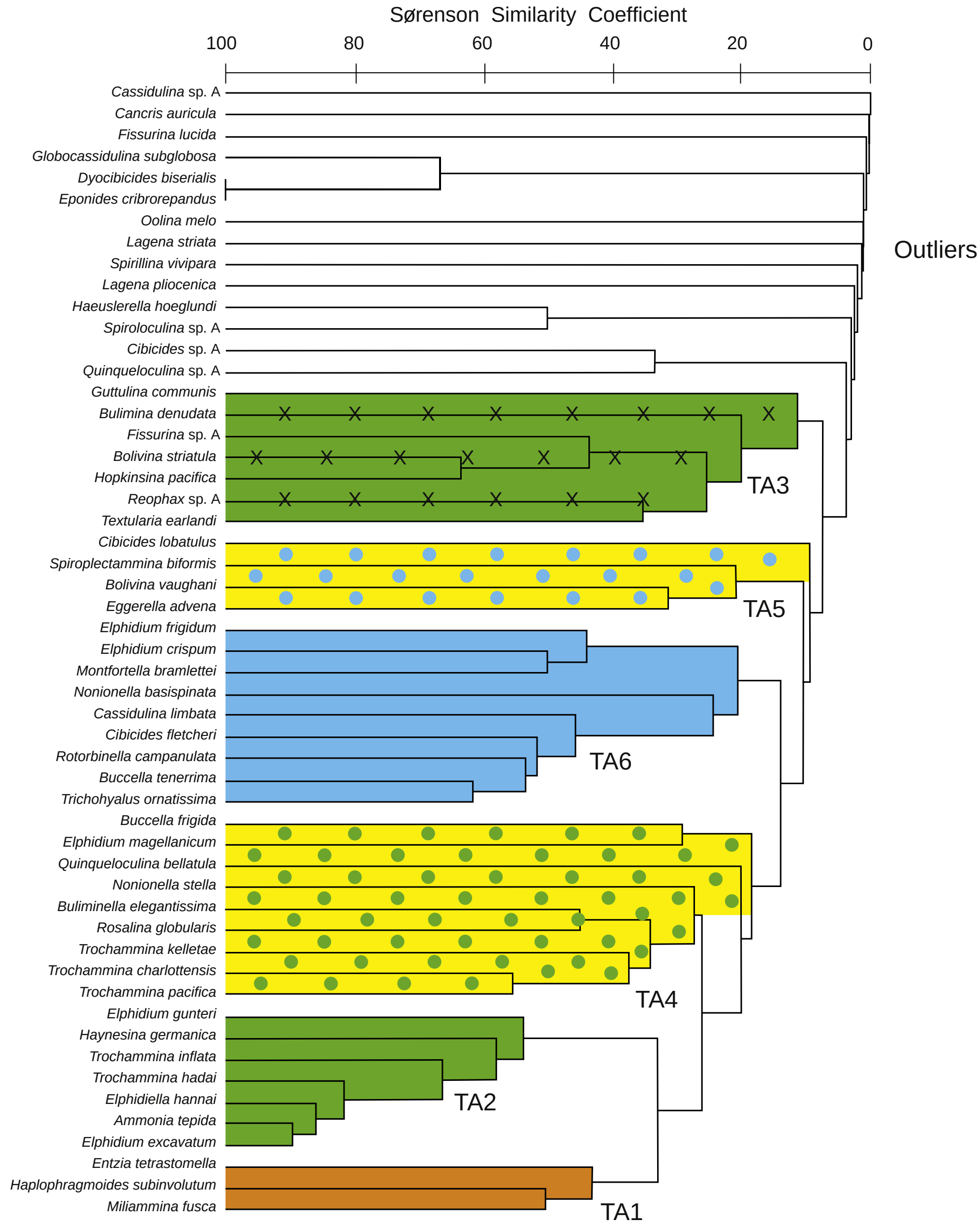


Fig. 8. Dendogram of the R-mode cluster analysis based on the presence/absence of the benthic foraminiferal species at the 1995–2010 San Francisco Bay Coastal System stations. Six taxonomic associations (TA) and 14 outliers are recognized.

excavatum, *Elphidiella hannai*, *Trochammina hadai*, and *Trochammina inflata*), but also has common brackish (*Haplophragmoides subinvolutum*, *Entzia tetrastomella*, and *Miliammina fusca*) and calcareous (*Elphidium gunteri* and *Haynesina germanica*) species as well. Clay and silt are the most common grain size in this subcluster.

Twenty-three stations constitute Subcluster SC2D. All but two of these stations are located in South Bay. They differ from SC2C in that they lack the brackish taxonomic component, instead having estuarine-dwelling *Bolivina striatula*, *Textularia earlandi*, and *Fursenkoina pontoni*, transitional estuarine/marine forms *Buliminella elegantissima* and *Rosalina globularis*, and several marine taxa, among them *Bulimina denudata*, *Fissurina* sp. A, *Rosalina globularis*, *Nonionella basispinata*, *Reophax* sp. A, and *Guttulina communis*. Grain size is variable in this subcluster, with silt and clay most common but sand dominates in some locations.

Thirty-one stations combined to form Station Cluster 3 (SC3; Fig. 9). The samples were recovered from 6 to 44 m water depth, averaging 20 m (Table 1). The sites are primarily located in Central Bay to the south and west of Angel Island. Additional sites include two on the San Francisco Bar, two west of Yerba Buena Island, and one in South Bay at Oyster Point. This is the most diverse (7–19 species/sample, averaging 13) fauna recovered in the study, although abundance is not high (BF# = 31), and living specimens comprised 3–57% (averaging 15%) of the fauna. As with SC2, *Ammonia tepida*, *Elphidiella hannai*, *Elphidium excavatum*, *Trochammina hadai*, and *Trochammina inflata* are dominant. Other common species present are *Haynesina germanica, Bolivina vaughani, Buccella frigida, Elphidium gunteri*, and *Trochammina kelletae*. In addition, several species typical of marine conditions (Bandy, 1953; Lankford and Phleger, 1973; Quinterno and Gardner, 1987; McGann, 2002) are abundant, including *Buccella tenerrima*, *Buliminella elegantissima*, *Cibicides fletcheri*, *Nonionella basispinata*, *Nonionella stella*, *Rosalina globularis*, *Rotorbinella campanulata*, *Trichohyalus ornatissima*, *Trochammina charlottensis*, and *Trochammina pacifica*.

Station Cluster 4 (SC4) is a compilation of 83 stations obtained between 5 and 70 m water depth, averaging 17 m (Fig. 9; Table 1).

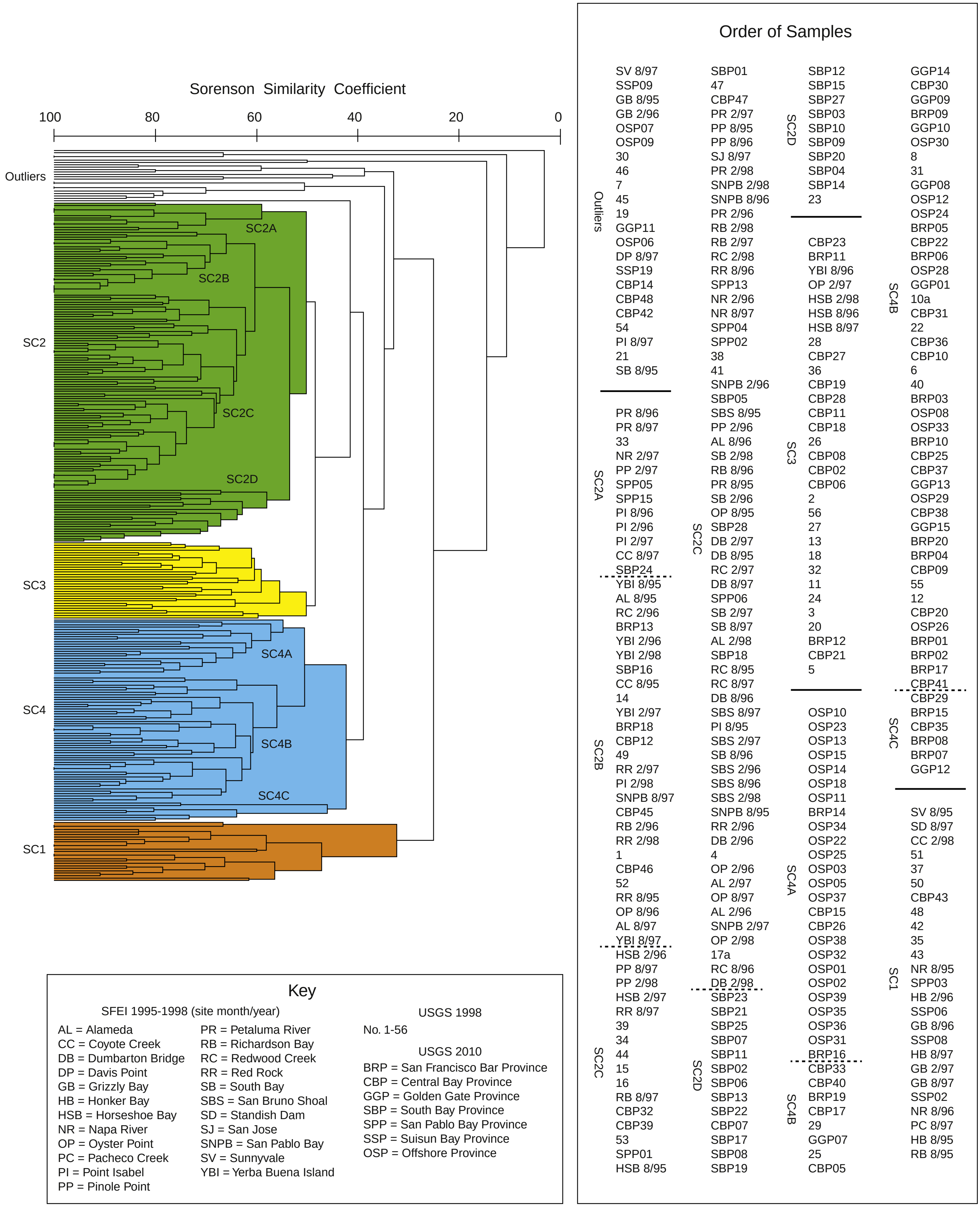


Fig. 9. Dendogram of the Q-mode cluster analysis based on the presence/absence of the benthic foraminiferal species at the 1995–2010 San Francisco Bay Coastal System stations. Four station clusters (SC) and 22 outliers are recognized.

The sites include those along the coast outside the estuary from Point Reyes to just south of Pedro Point, on the San Francisco Bar, in the vicinity of the Golden Gate, and in Central Bay primarily west of Angel Island. The species richness decreases slightly here (2–15 species/sample, averaging 7) as does the relative abundance of living specimens (0–25%, averaging 7%), whereas the foraminiferal abundance is substantially reduced (BF# = 2). The typical estuarine species (*Ammonia tepida, Elphidium excavatum*, and *Trochammina hadai*) are reduced in abundance, whereas those species that are adapted to living in turbulent conditions (Erskian and Lipps, 1987; McCormick et al., 1994), such as *Trichohyalus ornatissima* and *Rotorbinella campanulata*, are prevalent, as are *Elphidiella hannai* and the marine species *Buccella tenerrima*, *Cassiduina limbata*, *Cassiduina fletcheri*, *Elphidium frigidum*, and *Rosalina globularis*.

Station Cluster SC4 can be further subdivided into three subclusters (Fig. 9). All of the stations are similar in that they have abundant primary species *Ammonia tepida*, *Elphidiella hannai*, and *Trichohyalus ornatissima*. In addition, most stations in Subcluster SC4A have *Buccella tenerrima*, *Cassidulina limbata*, *Elpidium excavatum*, *Elphidium frigidum*, *Rosalina globularis*, *Cibicides fletcheri*, and *Rotorbinella campanulata*, but no *Trochammina hadai*. The fauna of Subcluster SC4B is comparable but *T. hadai* is abundant and fewer stations have *R. globularis*, *C. fletcheri*, or *R. campanulata*. Finally, Subcluster SC4C is quite distinct in that it has almost no secondary species.

Twenty-two stations obtained between 2 and 58 m water depth did not group with the other clusters and are referred to in this study as outliers (Fig. 9; Table 1). These samples were obtained in low-salinity waters near the confluence of the Sacramento and San Joaquin Rivers, in Grizzly Bay, and at Pacheco Creek and Davis Point in North Bay. They are also located at the SFEI sites of Sunnyvale and South Bay at the extreme southern end of South Bay, in turbulent waters in western Central Bay, as well as one site at both Point Isabel in eastern Central Bay and near the Golden Gate, and two sites along the outer coast. The abundance of foraminifera is highly variable at these stations (BF# 0.01–1387, average = 0.2), but all have foraminiferal faunas characterized by low species richness (1–9 species/sample, averaging 3); commonly only one or two species were recovered (Appendix 4). Living specimens range from 0 to 100% (averaging 43%), but these relative abundances are meaningless considering the small sample sizes at most of these stations.

Three principal components (PC) explained about 68% of the variance in the 1995–1998 SFEI environmental (E) data of water depth, pH, %TOC, bottom water temperature, bottom water salinity, dissolved oxygen, and grain size (Appendix 5): (E)PC1 (38%) is dominated by positive loadings of clay, silt, and %TOC, as well as negative loadings of sand and water depth; (E)PC2 (18%) is positively loaded for dissolved oxygen and negatively loaded for bottom water temperature and salinity; and (E)PC3 (12%) is positively loaded for gravel + shell and negatively loaded for pH. In contrast, the PCA of the foraminiferal/environmental (F/E) data for 1995–1998 was not nearly as successful, with four PCs explaining only 38% of the variance (Appendix 6): (F/E)PC1 (17%) has positive loadings for clay, silt, and %TOC and negative loadings for sand, water depth, and transitional estuarine to offshore (T4–T6) species; (F/E)PC2 (8%) has positive loadings for salinity, sand, gravel + shell, and two of the most common species (*Trochammina hadai* and *Ammonia tepida*) and negative loadings for silt and brackish (TA1) species; and (F/E)PC3 (7%) has positive loadings for estuarine (TA2) species and clay, silt, and %TOC and negative loadings for sand and *Buliminella elegantissima*; (F/E)PC4 (6%) has positive loadings for other transitional to offshore (T4–T6) species and bottom water temperature and a high negative loading for dissolved oxygen.

5.2. Other organic constituents

A wide variety of biologic remains besides benthic foraminifera were also found in the sediment samples (Appendix 2), including 19 species of ostracods (Appendix 7), eight species of diatoms (*Actinoptychus* sp., *Arachnoidiscus*? sp., *Campylodiscus* sp., *Coscinodiscus* sp./*Thalassiora* sp., *Cymbella* sp., *Isthmia nervosa*, *Melosira?* sp. and *Triceratium* sp.; Appendix 7), spumellarian radiolarians, thecamoebians, planktic foraminifera, and recrystallized fossil planktic foraminifera and radiolarians (Appendix 2). In addition, fragments from bony and cartilaginous fish, including vertebrae, mandibles, teeth, and dermal denticles were recovered in 106 samples. The remains of invertebrate macrofauna are also widespread (Appendix 2). Shell fragments occurred in nearly every sample, most of which are attributable to barnacles and bivalve mollusks; whole bivalve mollusks were prevalent in most samples as well with at least 12 distinct taxa identified (Appendix 8). A minimum of 12 species of gastropod are represented in 81 samples (Appendix 8), whereas gastropod opercula were rarely encountered, occurring at only three sites: Richardson Bay, Central Bay, and Coyote Creek. Remains of bryozoa and echinoid spines (white, pink, and purple varieties) commonly occur both inside and outside of the estuary, and worm tubes composed of either sand or mud are rare. Crab claws were also recovered at seven sites, one in South Bay, five in Central Bay, and one in the coastal offshore area. Floral remains ≥0.063 mm include woody stems, roots, spores, and seeds.

6. Inorganic constituents

6.1. Anthropogenic

Two types of microscopic man-made objects were recovered in the sediments. The first was welding slag, which is a byproduct of welding and is the residue left on a weld bead from the flux or globules of molten metal that resolidify on the metal surface. Such residues are usually chipped away with a hammer upon completion of the welding, thereby being released into the environment. Welding slag was recovered at 14 sites (Fig. 10; Appendix 2), widely distributed in western Central Bay in the vicinity of the docks on the northern side of San Francisco Bay, near Alcatraz Island, east of Angel Island, in Horseshoe Bay, at Red Rock, Pinole Point, in one sample out on the San Francisco Bar, and in South Bay near Alameda. The second was glass microspheres, which are used for a variety of purposes, including decorative glass products, coating movie screens, impact blasting, functional fillers in engineering polymers, increasing lubricity in drilling mud for oil well drilling, and for hospital flotation beds for burn victims (Glass balls, 2012). Their most widespread use today are as Potters' highway safety marking spheres ("highway spheres"; first used in 1934), which are sprinkled on top of, or mixed into, road striping and pavement marking material to increase retroreflectivity and improve highway safety. In this study, they were found in the sediment at 26 sites (Fig. 10; Appendix 2): Grizzly Bay, Pacheco Creek, in the Bay just off the Napa and Petaluma Rivers, Pinole Point, San Pablo Bay, Richardson Bay, Horseshoe Bay, Red Rock, east of the Tiburon Peninsula, near the northern San Francisco docks, east of Treasure Island, Alameda, San Bruno Shoal, Redwood Creek, Coyote Creek, San Jose, and in one sample from both the San Francisco Bar and the offshore coastal region.

6.2. Volcanic ash

Colorless, and occasionally brownish bubble-wall, bubble wall junction, and moderately to well-vesiculated, ribbed pumiceous volcanic glass shards were found in 78 samples throughout San Francisco Bay and in possibly five others (Fig. 11; Appendix 2). The disseminated shards were found in North Bay primarily along the channel but also as far away as the Petaluma River and possibly Grizzly Bay, and at seven sites in South Bay as far south as the SFEI site of South Bay. The highest abundance of glass shards were recovered in Central Bay, through the Golden Gate, and out on the San Francisco Bar. At key sites (USGS-J-1-98-SF-3, USGS-J-1-98-SF-28, USGS-J-1-98-SF-47, SFEI-8/95-PINOLE, and SFEI-8/95-RED ROCK-BC60), electron microprobe

Table 1

Station cluster (SC) Benthic foraminiferal biofacies No. of samples	Water depth range (m) Mean depth (m)	Species richness range Average species richness (species/sample)	Benthic foraminiferal no. (no. species/sample)	Living specimens range (%) Average living specimens (%)	Representative benthic foraminiferal species (percentage of samples with species present in the SC/biofacies)	Average % TOC	Average % Clay Average % Silt Average % Sand Average % Gravel + Shell
SC1 Brackish shallow subtidal 25	<1-9 $\overline{x} = 5$	1-7 $\overline{x} = 4$	16	0-38 $\overline{x} = 17$	*Ammonia tepida* (44) *Entzia tetrastomella* (36) *Haplophragmoides subinvolutum* (72) *Miliammina fusca* (52) *Trochammina hadai* (48) *Trochammina inflata* (92)	1.28	39.77 38.19 21.92 0.00
SC2 Estuarine shallow subtidal 142	1-35 $\overline{x} = 9$	2-20 $\overline{x} = 8$	230	0-56 $\overline{x} = 11$	*Ammonia tepida* (99) *Elphidiella hannai* (74) *Elphidium excavatum* (91) *Elphidium gunteri* (49) *Entzia tetrastomella* (21) *Haplophragmoides subinvolutum* (33) *Haynesina germanica* (58) *Miliammina fusca* (28) *Quinqueloculina bellatula* (16) *Trochammina hadai* (96) *Trochammina inflata* (84) *Trochammina kelletae* (21)	1.03	37.82 31.90 27.04 3.18
SC3 Estuarine intermediate/ deep subtidal 31	6-44 $\overline{x} = 20$	7-19 $\overline{x} = 13$	31	3-57 $\overline{x} = 15$	*Ammonia tepida* (100) *Bolivina vaughani* (32) *Buccella frigida* (25) *Buccella tenerrima* (61) *Buliminella elegantissima* (68) *Cibicides fletcheri* (45) *Elphidiella hannai* (100) *Elphidium excavatum* (97) *Elphidium gunteri* (45) *Haynesina germanica* (39) *Nonionella basispinata* (19) *Nonionella stella* (32) *Rosalina globularis* (61) *Rotorbinella campanulata* (71) *Trichohyalus ornatissima* (26) *Trochammina charlottensis* (58) *Trochammina hadai* (94) *Trochammina inflata* (65) *Trochammina kelletae* (42)	0.51	9.01 11.35 67.46 12.22
SC4 Nearshore marine 83	5-70 $\overline{x} = 17$	2-15 $\overline{x} = 7$	2	0-25 $\overline{x} = 7$	*Ammonia tepida* (81) *Buccella tenerrima* (76) *Buliminella elegantissima* (17) *Cassidulina limbata* (36) *Cibicides fletcheri* (39) *Elphidiella hannai* (100) *Elphidium excavatum* (81) *Elphidium frigidum* (20) *Rotorbinella campanulata* (43) *Trichohyalus ornatissima* (60) *Trochammina hadai* (37)	0.13	1.02 2.22 91.50 5.26
Outliers 22	2-58 $\overline{x} = 18$	1-9 $\overline{x} = 3$	0.2	0-100 $\overline{x} = 43$	*Ammonia tepida* (43) *Elphidiella hannai* (62) *Elphidium excavatum* (18) *Trochammina hadai* (43) *Trochammina kelletae* (24)	0.64	13.87 10.99 68.86 6.32

analyses show that all of the disseminated volcanic glass samples are heterogeneous and contain reworked Miocene to Holocene glass shards derived and transported from widespread volcanic eruptive source areas (Appendix 9). Because calcium and iron are the most stable of the nine analyzed major and minor elements, the oxides of these elements are particularly useful for identifying tephra and the weight-percent of each in the five samples is reported below.

USGS-J-1-98-SF-3 is a polymodal sample comprised of a mixture of early Miocene and Pliocene shards chemically correlated to tephra from the Miocene Sonoma volcanic field (%CaO = 0.70 and %Fe_2O_3 = 1.33), widespread western U.S. Miocene–Pliocene localities (%CaO = 0.58 and %Fe_2O_3 = 0.92), and the ~3.27 Ma Nomlaki Tuff Member of the Tuscan Formation (%CaO = 0.87–1.12 and %Fe_2O_3 = 1.02–1.21; source area: Mount Lassen, northeastern California). USGS-J-1-98-SF-28 is trimodal; the primary compositional mode consists of glass shards that match well with the Pliocene Nomlaki Tuff (%CaO = 0.89 and %Fe_2O_3 =1.00). Two minor modes contain unidentified shards. USGS-J-1-98-SF-47 is largely bimodal. The main subpopulation is composed of Holocene glass shards that closely match tephra from the Mono Craters volcanic field (%CaO = 0.54 and %Fe_2O_3 = 1.11). The minor subpopulation consists of shards from the Nomlaki Tuff (%CaO = 0.90 and %Fe_2O_3 = 1.04). SFEI-8/95-PINOLE also contains the ~3.27 Ma Nomlaki Tuff (%CaO = 0.92 and %Fe_2O_3 = 1.03), and three small unidentifiable volcanic glass subpopulations. Finally,

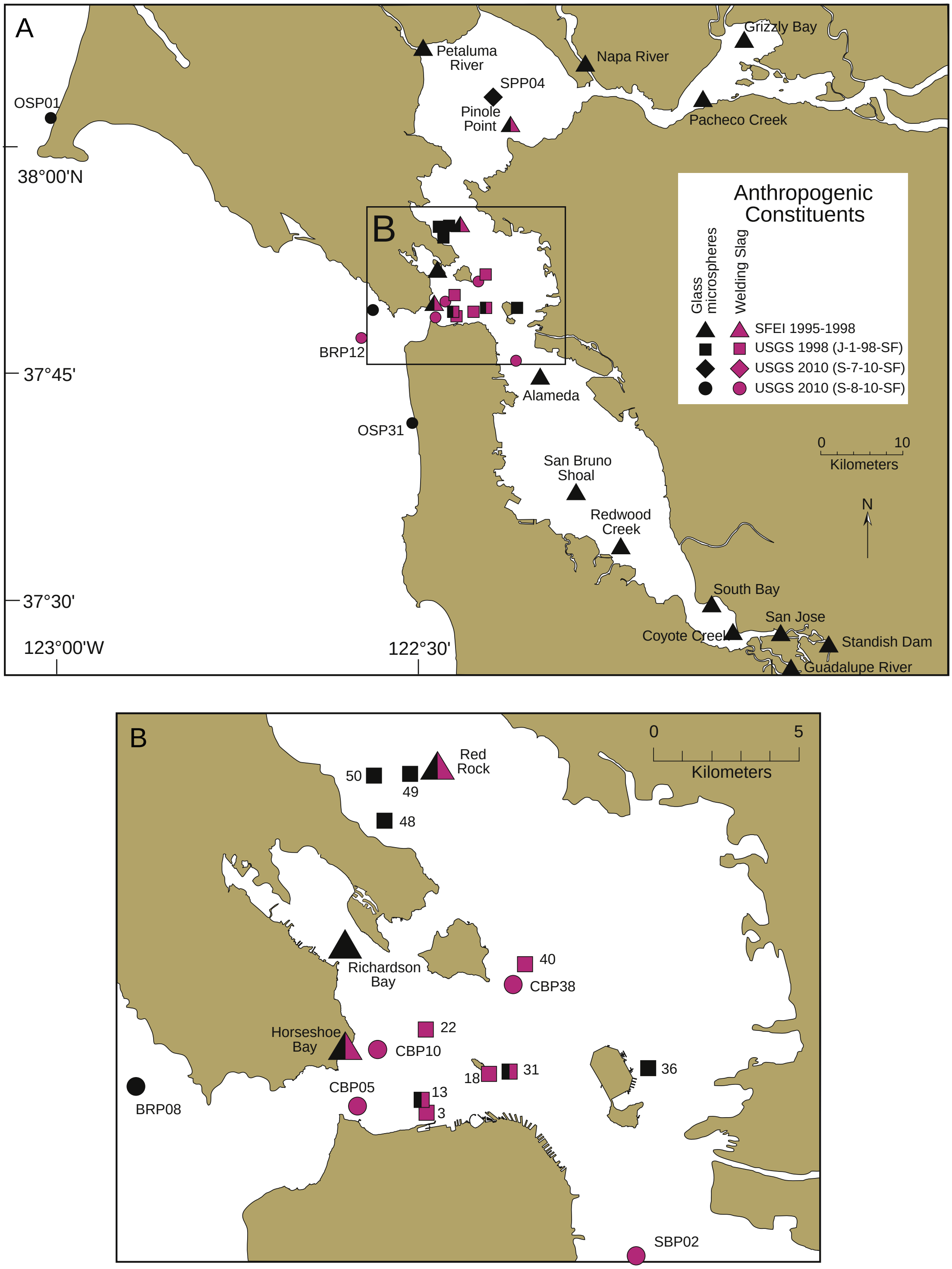


Fig. 10. Spatial distribution of the anthropogenic constituents (glass microspheres and welding slag) at the 1995–2010 San Francisco Bay Coastal System stations. B. Detailed map of the stations in Central Bay, the Golden Gate, and the eastern portion of the San Francisco Bar. Bicolored symbols represent stations where both constituents are present.

SFEI-8/95-RED ROCK-BC60 is polymodal and contains reworked shards that correlate to early Miocene to Pliocene tephra from the Great Valley of California (Valley Springs Formation; %CaO = 0.51 and $\%Fe_2O_3 = 0.90$), Mount Lassen area of northeastern California (Nomlaki Tuff; %CaO = 0.89–1.12 and $\%Fe_2O_3 = 0.98–1.18$), and from the Sonoma volcanic field in northern California (%CaO = 0.67 and $\%Fe_2O_3 = 1.31$).

There are no known outcrops or discrete deposits of the above, identified volcanic ashes near or in their respective core sites. Knowing the provenance of a tephra and how proximal or distal its depositional sites are relative to the volcanic source areas is helpful in determining the magnitude and areal distribution of an eruption. Determining whether a volcanic ash is homogeneous and primary air-fall, or was transported by erosion, wind, and/or water as well as

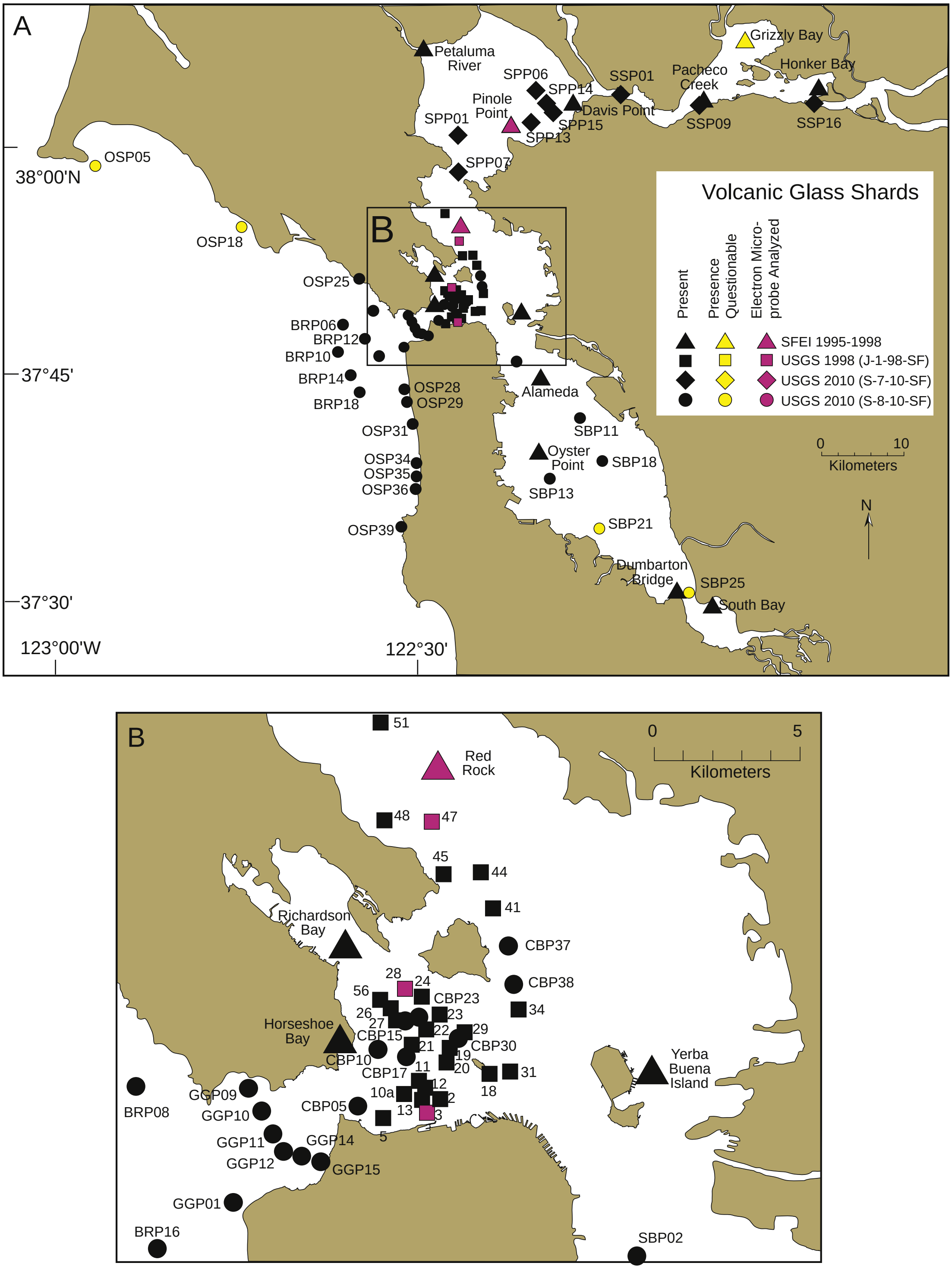


Fig. 11. Spatial distribution of volcanic glass shards at the 1995–2010 San Francisco Bay Coastal System stations. B. Detailed map of the stations in Central Bay, the Golden Gate, and the eastern portion of the San Francisco Bar.

reworked and heterogeneous permits reconstruction of local and regional earth surface processes.

7. Discussion

7.1. Hydraulic transport

Foraminifera are equivalent in size to sand-sized mineral particles (Phleger et al., 1953; Sandifer, 1969). However, laboratory studies have shown that the crtitical shear velocities necessary to entrain dead (empty) tests are lower than those of mineral grains of the same size (Brush and Brush, 1972; Pettijohn, 1975). For benthic species, the velocities are <10 cm/s (Kontrovitz et al., 1978, 1979; DePatra and Levin, 1989) and for planktic species, generally ~2 cm/s (Berger and Piper, 1972). Whereas empty tests are passively entrained based on their size, shape, and density in relation to the bottom current velocity, suspension of living benthic foraminiferal tests may be more difficult due to attachment of their pseudopodia to the substrate (Severin and

Lipps, 1989) or because many live infaunally (Corliss, 1985; Ozarko et al., 1997). Bottom currents with velocities > 10–15 cm/s are probably necessary to entrain living tests in most environments (Alve, 1999), except in fluffy sediments (e.g., phytodetritus) where currents of only ~7 cm/s may be necessary (Lampitt, 1985). Furthermore, foraminiferal tests will behave differently than terrigenous particles during transport (Stow et al., 1984), being selectively entrained and differentially deposited due to their size, weight, and shape-dependent hydraulic behaviors (Berger and Piper, 1972; Kontrovitz et al., 1978, 1979; Brunner and Normark, 1985; Kontrovitz and Snyder, 1981; Brunner and Ledbetter, 1987). The same can be said about the other biologic, anthropogenic, and volcanic constituents recovered in this study. All are sand size, low-density, and in shapes that are easily tranported by the currents in the estuary and nearby coastal area that are characterized by velocities on the order of m/s instead of cm/s. Combining our knowledge of where these sedimentological constituents originated and eventually were recovered will help us to understand the pathways of sediment transport in the San Francisco Bay Coastal System.

7.2. Benthic foraminiferal biofacies, diversity, and environmental conditions

Clustering of the species (R-mode) recovered in the samples (Fig. 8), as well as indicative species associated with the cluster of stations (Q-mode) which identified the same groups of species (Fig. 9), enables us to define four distinct benthic foraminiferal biofacies and several outliers for the San Francisco Bay area from 1995 to 2010. The four biofacies are the Brackish Shallow Subtidal, the Estuarine Shallow Subtidal, the Estuarine Intermediate/Deep Subtidal, and the Nearshore Marine. Spatial distribution of these four biofacies is presented in Fig. 12. The environmental (abiotic) factors associated with these biofacies are also discussed.

Typically, marsh to very shallow, brackish subtidal estuarine environments are stressful on biological organisms because of wide fluctuations in water temperature and salinity as well as high organic input. As a result, these environments are often characterized by faunas with low species richness, dominanted by agglutinated taxa because calcareous tests are dissolved in low pH sub-surface sediments and preservation is poor (Phleger, 1967; Jennings and Nelson, 1992; Jonasson and Patterson, 1992). Previous studies demonstrated that agglutinated taxa (i.e., *Haplophragmoides subinvolutum*, *Miliammina fusca*, and *Entzia tetrastomella*) dominate the faunas in the shallow regions of the estuary characterized by low salinity and low velocity currents, such as Suisun, Grizzly, and Honker Bays (Slater, 1965), the perimeter of San Pablo Bay (Locke, 1971), northern Richardson Bay (Connor, 1975), the marshes of eastern Central Bay (Weber and Casazza, 2006), and the western and eastern peripheries and extreme southern end of South Bay (Quinterno, 1968; Arnal et al., 1980). Similarly, the 1995–2010 stations (SC1) that are dominated (i.e., recovered in 36–92% of the samples of the cluster; Table 1) by these same agglutinated taxa (TA1), as well as the agglutinated species *Trochammina inflata* and *Trochammina hadai* (48%), are assigned to the Brackish Shallow Subtidal Biofacies and are situated in generally the same locations (Fig. 12). Reflecting the challenging environment, the fauna is characterized by the lowest species richness (averaging 4 species/sample) of any found in this study. The sites are shallow (<1–9 m, averaging 4 m) and many are brackish to nearly fresh seasonally (Fig. 4). They are also the most fine-grained (averaging 40% clay; Fig. 3) and organically-rich (averaging 1.28 %TOC) sediments encountered in the study (Table 1). This trend of decreasing grain size with increasing sediment carbon can be attributed to the fact that organic matter is attracted to fine-grained sediment because organic matter adsorbs onto mineral surfaces (CSIRO Huon Estuary Study Team, 2000) and was not only seen in these marginal environments but throughout San Francisco Bay (i.e., from 1995 to 1998 illustrated by the two PCAs with both (E)PC1 and (F/E)PC1 associating clay, silt, and %TOC and (F/E)PC2 associating these abiotic factors with a brackish (TA1) fauna [Appendix 6)] and continuing into 2010 [Fig. 13a]). Two of the fine-grained sites associated with this biofacies (i.e., Honker Bay and Grizzly Bay) are also characterized by acidic conditions with pH < 7. In addition, the stations of the Brackish Shallow Subtidal Biofacies are characterized by water with the highest amount of dissolved oxygen during the winter (Appendix 1) when they receive input from riverine sources, which agrees with the observation that cold, fresh water can hold more dissolved oxygen than warm, salty water (University of Rhode Island, 2001) and is supported by PCA components (E)PC2 and (F/E)PC4 in which dissolved oxygen varies inversely with water temperature and salinity; Appendices 5, 6).The occurrence of many rose Bengal-stained individuals (average 17%; maximum 38%; Appendix 4) in this biofacies suggests they were not transported but were living there.

The Estuarine Shallow Subtidal Biofacies is located in the ecologically more stable, slightly deeper (averaging 9 m; Table 1), more saline waters of central San Pablo Bay, the middle and eastern portions of Central Bay, and all but the southern end of South Bay (SC2, Figs. 4, 12). As with the Brackish Shallow Subtidal Biofacies, fine-grained sediment is the most prevalent (37.82% clay; Fig. 3) and the sediment is enriched in organic carbon (averaging 1.03 %TOC), although both are slightly lower than in the previous biofacies (Table 1). The (F/E)PC3 component of the PCA associated estuarine species (TA2) with clay, silt, and %TOC (Appendix 6) as well. There are also several sites where acidic sediment was encountered (Napa River, Pinole Point, Richardson Bay, Oyster Point, San Bruno Shoal, and Dumbarton Bridge), all within regions of the Bay with reduced current activity and decreasing grain size (Fig. 13b).

Species richness is higher (averaging 8 species/sample) in this biofacies than in the Brackish Shallow Subtidal Biofacies and it is dominated by the calcareous taxa *Ammonia tepida* (99%), *Elphidium excavatum* (91%), *Elphidiella hannai* (74%) and *Haynesina germanica* (58%), as well as the agglutinated non-native taxon *Trochammina hadai* (96%) (TA2; Table 1). A high percentage of these foraminifera were alive (average 11%; maximum 56%; Appendix 4) when the samples were acquired, suggesting they were not transported to this region. Previous studies have also documented the presence of a predominantly calcareous fauna at these locations (Quinterno, 1968; Locke, 1971; Wagner, 1978; Arnal et al., 1980; McGann and Sloan, 1999). *Ammonia tepida* and *E. excavatum* are common inhabitants of estuaries worldwide (Murray, 1973, 1991). Arnal et al. (1980) considered the presence of *E. hannai* to be indicative of marine water, and since they found the species most abundant in the coarse sediment associated with the deep channel (12–22 m) of South Bay, they suggested that oceanic water was present in this channel for most of the year. They also found *H. germanica* (as *Elphidium incertum obscurum*) most often associated with finer-grained sediment and preferentially occupying regions with high organic matter (>2%) in South Bay (Arnal et al., 1980). *Trochammina hadai* thrives in shallow estuarine waters in Japan and elsewhere along the eastern Pacific seaboard (McGann et al., 2000).

Low salinity-indicating native agglutinated taxa comprising TA1 also occur in the Estuarine Shallow Subtidal Biofacies, although less commonly (21–33%, except for *Trochammina inflata* at 84%) than in the Brackish Shallow Subtidal Biofacies. However, because these agglutinated species were recovered far from their preferred marginal-marine habitats and very rare living specimens were present (*Miliammina fusca* at three locations: SPP04, SPP05, and SBP28), we suggest that they were not recovered *in situ* but transported from the periphery to the middle of these subembayments. In contrast, a variety of offshore taxa were also recovered at four sites east of Angel Island in Central Bay and at 15 sites in South Bay associated with this biofacies. Many of these were alive, suggesting that they were transported into the Bay from the oceanic realm. Living *Bulimina denudata*, *Nonionella basispinata*, *Nonionella stella*, and *Rotorbinella campanulata* were found at three or more sites, *Fissurina* sp. A and three species of *Trochammina* (*T. pacifica, T. charlottensis, and T. kelletae*) at two, and *Guttulina communis* and *Reophax* sp. A at one. Species which typically inhabit ocean outlet regions of estuaries or marine environments were also found alive, including *Rosalina globularis* (9)

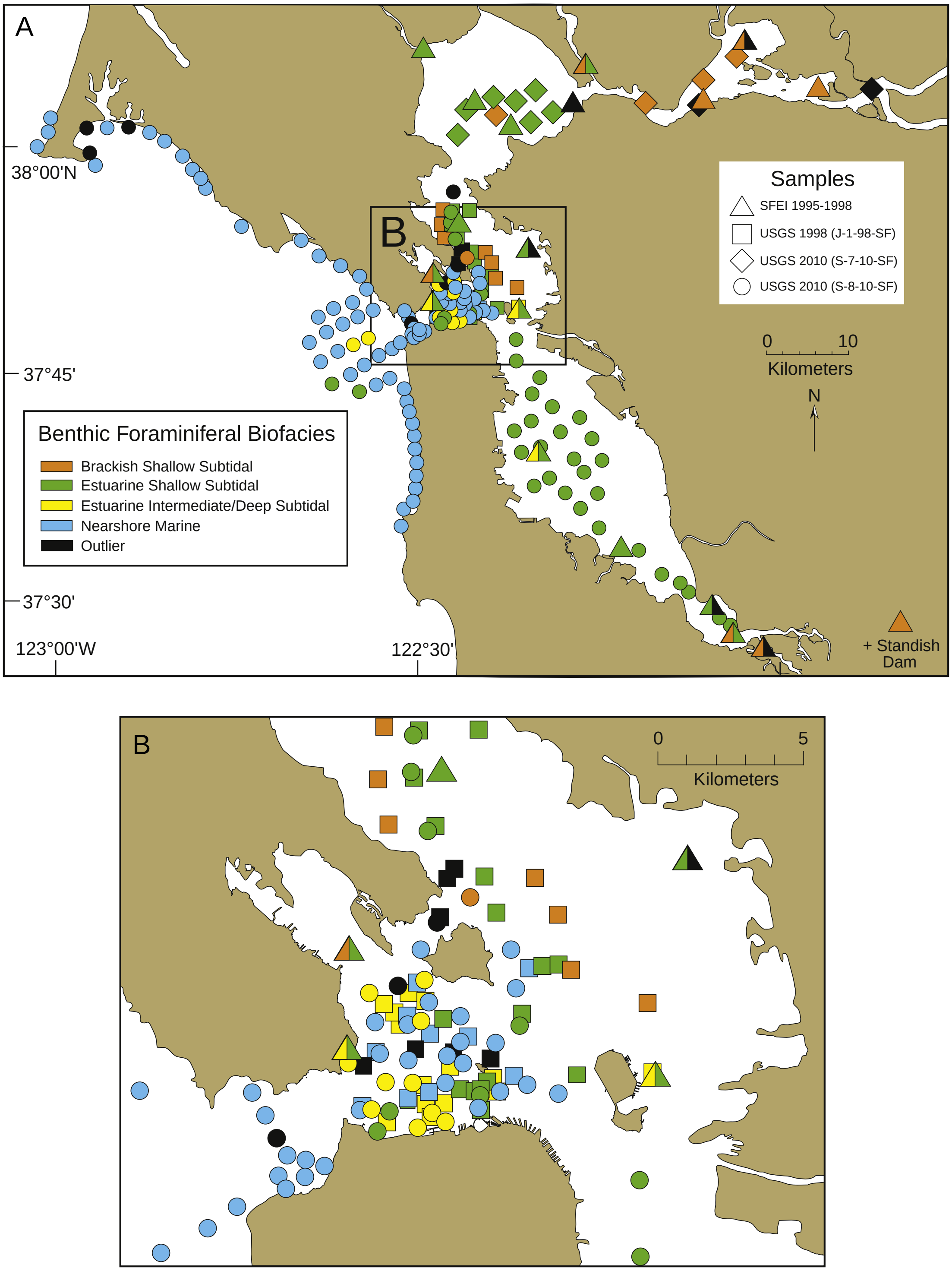


Fig. 12. Spatial distribution of the benthic foraminiferal biofacies identified by the R- and Q-mode cluster analyses of the 1995–2010 San Francisco Bay Coastal System stations. B. Detailed map of the stations in Central Bay, the Golden Gate, and the eastern portion of the San Francisco Bar. Bicolored symbols represent stations where two biofacies are present.

and *Buliminella elegantissima* (7). Dead tests of these same species were also found at many additional sites, as were a few species that were never found alive: *Haeuslerella hoeglundi*, *Spirillina vivipara*, *Spiroloculina* sp., and *Elphidium crispum*, the latter of which resides in the littoral zone of the open-ocean coast outside the estuary (Schenck, 1940; Lankford and Phleger, 1973).

Several stations associated with the Estuarine Shallow Subtidal Facies are located near sites where dredging and the disposal of sediment have occurred in the estuary over the last century (see discussion in Barnard et al., 2013–in this issue-a). One station (SBP12) is situated along the western edge of South Bay in the general vicinity where dredging still occasionally occurs. Three other stations in Central Bay (15, 16, and 17a) were obtained in proximity to the Alcatraz dredge disposal site southwest of Alcatraz Island which was heavily used until 1987 when the height of the mound was deemed a potential navigational hazard, resulting in a change in policy that greatly reduced the amount, frequency, and character of the sediment disposed there (Chin et al., 2004; LTMS, 1995). Since the majority of the dredge material is now disposed of in the Pacific Ocean (DMMO, 2008; Keller, 2009; San Francisco Estuary Institute, 2009) and none of these stations are

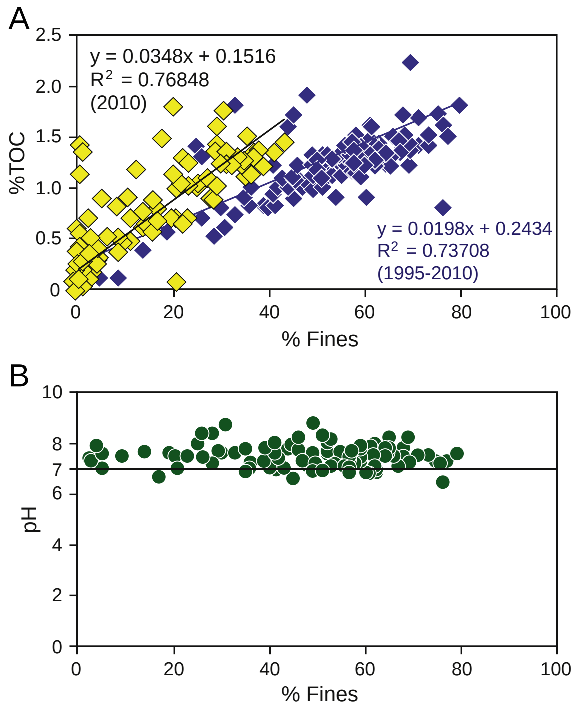


Fig. 13. A. Plot of percent total organic carbon versus percent fine-grained sediment for 2010 and 1995–2010. Trendlines are presented for each. B. Plot of pH versus percent fine-grained sediment for samples collected from 1995 to 1998.

characterized by species richness or abundance that differs greatly from neighboring stations, it does not appear that these activities have had a major impact on the transport of allochthonous taxa to these sites.

The subclusters of SC2 appear to have identified stations that are related by both environmental parameters and sediment transport. They all are characterized by the primary estuarine species *Ammonia tepida*, *Trochammina hadai*, and *Trochammina inflata*, but have differing secondary species and grain size. Subcluster SC2A stations occur in the marginal estuarine areas of San Pablo Bay, the eastern region of Central Bay, and the southern portion of South Bay with estuarine (TA2) as well as a few brackish (TA1) species that are influenced by lower salinity and grain size which is predominantly clays and silt; that is, areas of little current action where sediment transport is negligible. Subcluster SC2B stations have common estuarine (TA2) species and are located in Central and South Bays with abundant sand, for which *Elphidiella hannai* seems to have an affinity. The stations of this subcluster are subjected to higher current velocity with little transport from the surrounding brackish regions. Subcluster SC2C stations are the most common of the cluster and are characterized by clay- and silt-rich sediment with abundant calcareous (TA2) and agglutinated (TA1) taxa. These stations are situated throughout San Francisco Bay where the intensity of the current action is intermediate between that associated with SC2A and SC2B and the transport of allochthonous agglutinated species from surrounding brackish regions occurs. In contrast, Subcluster SC2D is unique in that is has no brackish fauna but common estuarine, transitional estuarine, and marine species, and occasional dominance by sand in an otherwise clay- and silt-dominated environment. Although situated almost entirely in South Bay, the faunas of these stations have a significant marine signature, indicating transport from the marine realm. Typically, species richness is found to increase with increasing sample size. Whereas the rarefaction analysis demonstrates that the expected number of species in sample sizes of 200–300 specimens from San Francisco Bay is ~7, the sample sizes in this subcluster are generally in this range (~300–350 specimens) but the average species richness is nearly 60% higher (12 species/sample) and at several stations (SBP02, SBP06, SBP11, SBP13, and SBP19) it is more than twice the average (15–20 species/sample). In contrast, some samples in other SC2 subclusters have far higher abundances (e.g., in August 1995, 1442 specimens at Point Isabel and 1550 specimens at Redwood Creek), but are characterized by nearly average species richness (7 and 9 species/sample, respectively). The evidence suggests that the addition of marine taxa to the already abundant estuarine fauna in South Bay, not sample size, is responsible for the high average foraminiferal abundance (BF# = 230) in the Estuarine Shallow Subtidal Biofacies and also explains why subcluster SC2D of South Bay has the highest species richness of any of the SC2 subclusters.

The stations of the Estuarine Intermediate/Deep Subtidal Biofacies (SC3) are, on average, the deepest (20 m) found in this study and are characterized by a lower organic component (0.51 %TOC) and higher sand content (67.46%) than the previous biofacies, with the clay, silt and gravel fractions each contributing approximately 9–12% (Table 1; (E)PC1 and (F/E)PC1 positively associate clay, silt, and %TOC and negatively associate sand, water depth, and a transitional estuarine to offshore (TA4–TA6) fauna; Appendix 6). The foraminiferal abundance (BF# = 31) exceeds that of the mudflat and brackish regions but is far below that of the estuarine shallow subtidal areas (BF# = 230). Like the latter, however, this biofacies is also dominated by the common estuarine species (TA2) *Ammonia tepida* (100%), *Elphidium excavatum* (97%), *Trochammina hadai* (94%), *Elphidium gunteri* (45%), *Haynesina germanica* (39%), and *Bolivina vaughani* (32%). Living specimens of *A. tepida* were recovered at a third of the stations, whereas a fourth had both living *E. excavatum* and *T. hadai*, suggesting the species were residing there. Considering what is known about the distribution of these species in the estuary from previous studies (Quinterno, 1968; Wagner, 1978; Arnal et al., 1980; McGann and Sloan, 1999; McGann et al., 2000), their presence in Central and South Bays (Fig. 12) is expected. In contrast, the rare occurrence (in five samples or less, of which only one sample had a single living species) of the brackish-water indicating agglutinated species *Haplophragmoides subinvolutum*, *Miliammina fusca*, and *Entzia tetrastomella* (TA1) far from shore and at these depths is an anomaly that is, once again, attributed to sediment transport.

A diverse, transitional estuarine to marine fauna (TA4–TA6) characterizes the Estuarine Intermediate/Deep Subtidal Biofacies as well. Very abundant (58–100%) *Buccella tenerrima*, *Buliminella elegantissima*, *Elphidiella hannai*, *Rosalina globularis*, *Rotorbinella campanulata*, and *Trochammina charlottensis*, common (26–45%) *Cibicides fletcheri*, *Nonionella stella*, and *Trichohyalus ornatissima*, and significant (10–19%) abundances of *Nonionella basispinata* and *Cassidulina limbata* were recovered at the 1995–2010 stations (Table 1). Not surprisingly, *Buliminella elegantissima* and sand associated in the PCA (i.e., (F/E)PC3), as the taxon commonly resides on sandy continental shelves (Ingle, 1980; McGann, 2002). Rare occurrences of other marine taxa were also found at some western Central Bay sites, including *Lagena pliocenica* (CBP27 and 11), *Lagena striata* (56), and *Haeuslerella hoeglundi* (13). The depth range of *T. ornatissima* is from the intertidal zone to ~30 m water depth, with maximum abundance at <15 m (Lankford and Phleger, 1973). In the intertidal, the species lives on invertebrates and algae (Erskian and Lipps, 1987), or is associated with surf grass (Steinker, 1973); in the subtidal it occurs in the sediment (Erskian and Lipps, 1987). Bandy (1953) stated that on a transect off San Francisco Bay, *E. hannai*, *B. elegantissima*, and *N. stella* were the prevailing species in his Middle Neritic Zone (~35–110 m), and *N. stella*, *N. basispinata*, and *C. limbata*, among others, were the most abundant species in his Lower Neritic Zone (~120–200 m). Arnal et al. (1980) also considered *E. hannai* a marine species. In fact, over 90% of the 2010 sites assigned to the Estuarine Intermediate/Deep Subtidal Biofacies had living marine species, suggesting that sediment and the associated biological constituents are actively transported into the Bay from the offshore realm. The high species richness (7–19 species/sample, averaging 13) associated with this biofacies reflects the presence of autothonous estuarine and marine taxa, as well as allochthonous brackish species.

Samples assigned to the Nearshore Marine Biofacies (SC4) occur offshore along the coast, on the San Francisco Bar outside and through the Golden Gate, and in the turbulent areas of western Central Bay (Fig. 12). Sand is the most prevalent sediment type in these samples (91.50%) with gravel a distant second (5.26%; Fig. 3; Table 1). With the high-velocity currents flowing in an out of the estuary daily, it is not surprising that the organic content in the sediment and foraminiferal abundance are both low (0.13 %TOC and BF# = 2, respectively; Table 1). Species richness is comparable to that normally encountered in the Bay (2–15 species/sample, averaging 7), as both estuarine and marine taxa are common (TA2–TA6), moving back and forth with the tides. Many of the abundant species live in other nearby turbulent zones (e.g., the opening of Tomales Bay; Erskian and Lipps, 1987; McCormick et al., 1994), displaying adaptive strategies that improve their chances of survival. These strategies include robust tests that can withstand the pounding of wind-driven waves that impinge upon the shoreline (*Elphidiella hannai* in Alve, 1999; *Trichohyalus ornatissima* and *Rotorbinella campanulata* in Erskian and Lipps, 1987), continuous instead of seasonal reproduction (*Ammonia beccarii* in Basson and Murray, 1995, = *Ammonia tepida* in this study), temporary planktic reproductive stages in which float chambers are built to aid in dispersal (*Rosalina globularis* in Rückert-Hilbig, 1983), and the timing of reproduction to coincide with the presence of increased nutrients in surface waters associated with upwelling as well as reproduction by fusing tests during plastogamy (both associated with *T. ornatissima*, Erskian and Lipps, 1987). However, the living specimens (average 7%; Appendix 4) associated with this biofacies were almost exclusively marine taxa and the transitional estuarine/marine taxon *E. hannai*; very rare living representatives of *Elphidium excavatum* were present at only two sites, one in Central Bay and one offshore, and *A. tepida* at seven sites, two on the San Francisco Bar and five in western Central Bay.

Sediment transport may have influenced the manner in which the SC4 stations separated into subclusters. The stations associated with Subcluster SC4A are primarily located offshore with a few others from the San Francisco Bar and near the Golden Gate, and are characterized by offshore taxa and no estuarine-dwelling *Trochammina hadai*. Those in Subcluster SC4B have *T. hadai* and fewer occurrences of some of the offshore species, and are most commonly situated in the estuary in western Central Bay, although a few stations in this subcluster do occur offshore. However, those stations do not have *T. hadai* except for three (OSP26, OSP29, and OSP30) which are located near the opening of San Francisco Bay (Fig. 6). Finally, the stations of Subcluster SC4C have a nearly depauparate fauna with no secondary species. These distributions suggest the SC4A stations are generally those furthest from the Bay and least impacted by sediment transport through the Golden Gate. Stations of Subcluster SC4B are the most influenced by tidal action in that they have a diverse mix of estuarine and marine species, although the restricted presence of *T. hadai* outside the Bay suggests sediment is not transported very far north or south of the Golden Gate. And the stations with a depauparate fauna characteristic of Subcluster SC4C occur on the San Francisco Bar, through the Golden Gate, and into southwestern Central Bay where the currents are extreme, as reflected in a predominance of sand and gravel (Fig. 3). These extreme conditions are not conducive to the survival of foraminifera and is supported by their low abundance (BF# <0.35) in this region.

7.3. Radiolarians and planktic foraminifera

Radiolarians were recovered at many locations throughout the study area. Their occurrence is confirmed at 16 sites (10 in Central Bay, five in North Bay, and one in South Bay) (Fig. 14). In addition, recrystallized specimens were recovered in Suisun Bay (SSP09 and SSP16) and at seven sites in the coastal area. Planktic foraminifera were recovered at eleven sites (Fig. 14). Eight of these occur in Central Bay, one offshore, and two others are located as far north as Pinole Point in North Bay and the extreme end of South Bay. Recrystallized planktic foraminifera were also recovered in Suisun Bay (SSP16), Central Bay (30), as well as offshore (OSP07).

Radiolarians and planktic foraminifera only live in a fully marine, open-ocean environment, preferably just seaward of the continental break (Kling, 1978; Brasier, 1980; Hemleben et al., 1989). Their presence in San Francisco Bay sediments, therefore, must be attributed to transport from an oceanic setting. The radiolarians and planktic foraminifera may have been carried from the marine realm into the Bay by means of birds' feet and feathers (Resig, 1974; Patterson, 1987) or floating debris such as seaweed, logs, and man-made objects (Winston et al., 1997). However, their deep-water origin makes these vectors unlikely. A more plausible explanation is transport from the nearby Pacific Ocean through the Golden Gate with the strong flood tides (Fig. 2C). The presence of these marine elements in western Central Bay is readily attributed to their particle size and the deposition of sediment during the slack tide or as the flood tide flows through the Golden Gate and decreases quickly in velocity. The recovery of marine elements as far north as Honker Bay and to the extreme southern end of South Bay (Fig. 14) suggests that currents carry sediments from the offshore region to the farthest ends of San Francisco Bay.

7.4. Diatoms

Despite the fact that most of the diatom species that are environmentally indicative are in the silt- and clay-size fraction, previous studies have still used those >0.063 mm in size as a limited proxy for facies identification (Atwater et al., 1977; Sloan, 1992). Diatoms are abundant in most of the sediments in San Francisco Bay and eight species that often grow to sand-size were recovered in this study. *Isthmia nervosa* was the most common species, occurring at 59 sites (Fig. 14; Appendix 7). It is epiphytic, living attached to algae in tidepools in the high-energy, nearshore coastal marine zone (Laws, 1988). *Triceratium* sp. is another marine species, but it was recovered only once, in Honker Bay. *Campylodiscus* sp. is representative of a brackish to marine environment (Cholnoky, 1968) and was most often found in the quiet regions away from the channel. *Cymbella* sp. is a freshwater species that was recoverd at only three localities in Suisun and Honker Bays. And because the different species of *Actinoptychus* sp., *Arachnoidiscus*? sp., *Melosira* sp., and *Coscinodiscus* sp./*Thalassiora* sp. are affiliated with dissimilar environments or were questionably identified, little can be said of the environmental implication of these species' appearances in the San Francisco Bay Coastal System.

7.5. Ostracods

The species most commonly recovered in San Francisco Bay sediments are typical of brackish, estuarine environments, such as *Spinilebris hyalina*, *Cyprideis beaconensis*, and to a much lesser extent, *Physocypria globula* (Nichols and Thompson, 1985; Cohen et al., 2007). Representatives of these taxa occurred in Central Bay, South Bay, and North Bay as far east as Grizzly Bay (Fig. 15). Most often the specimens were recovered with both valves intact. Because valves open after death as the adductor muscles relax and decay, they are easily disarticulated by transport or bioturbation (Brasier, 1980). Therefore, the presence of articulated valves suggests the animals were living, the carapaces were not transported far from their place of origin, or they were deposited in areas where the rate of sedimentation was high (Oertli, 1971) when they were collected. In contrast, only a few disarticulated valves of *S. hyalina* and *C. beaconensis* were found outside the Bay at sites BRP12 and OSP35, respectively, suggesting they were transported to these sites.

Several other ostracods recovered in this study are indicative of the open marine environment, including *Aurila lincolnensis*, *Robustaurila jollaensis*, *Radimella aurita*, *Cytheromorpha grandwashensis*, *Hemicythere hazeli*, and *Ambostracon* sp. (Swain and Gilby, 1974; Valentine, 1976). These species were most often found in western Central Bay (Fig. 15),

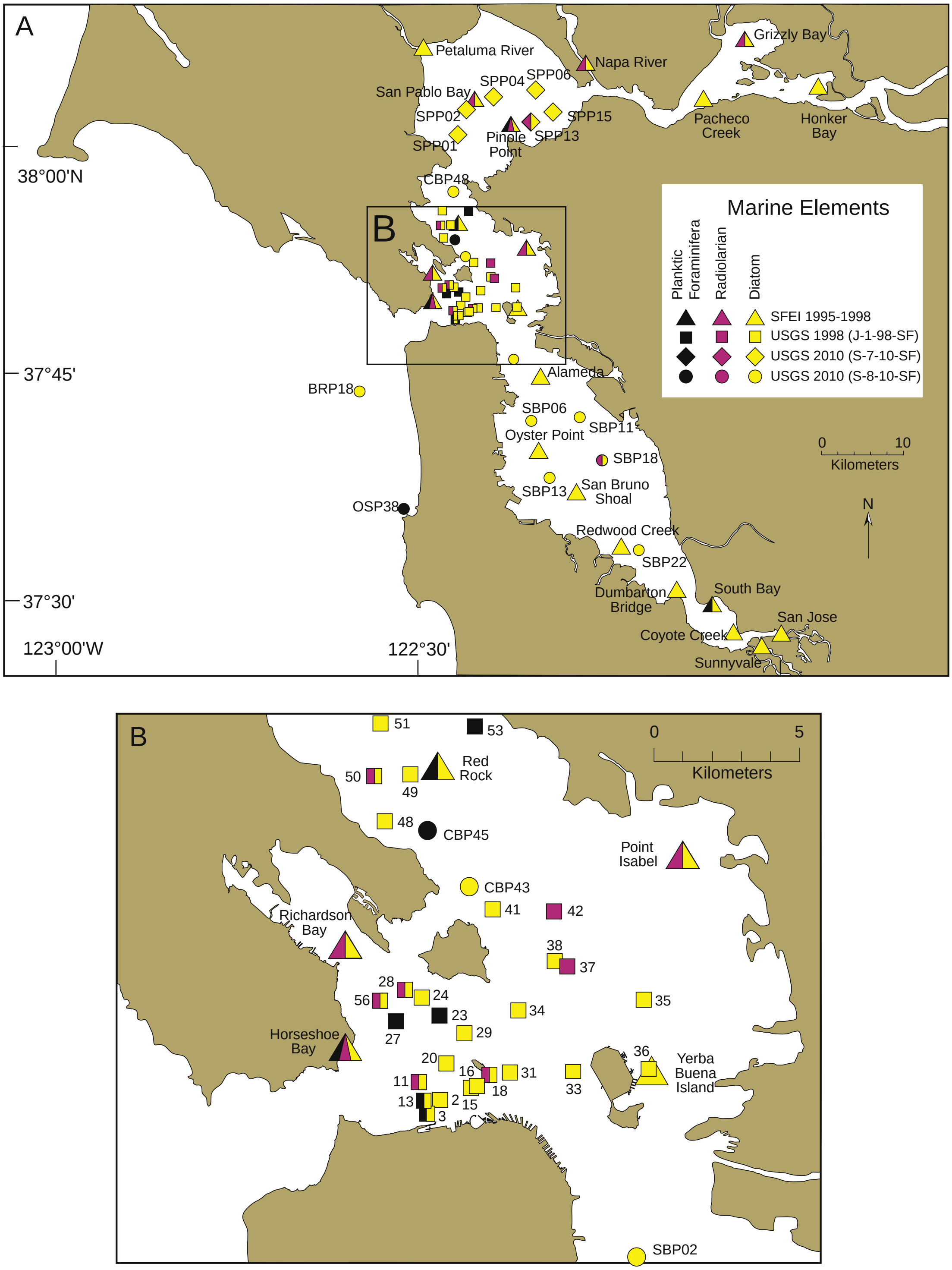


Fig. 14. Spatial distribution of marine-indicating planktic foraminifera, radiolarians, and diatoms at the 1995–2010 San Francisco Bay Coastal System stations. B. Detailed map of the stations in Central Bay, the Golden Gate, and the eastern portion of the San Francisco Bar. Bi- and tri-colored symbols represent stations where two or three constituents are present, respectively.

although a few specimens were also found down the length of South Bay to south of the Dumbarton Bridge, in San Pablo Bay between Pinole Point and Davis Point, and at two locations outside San Francisco Bay (BRP16 and OSP35). In contrast to the estuarine species recovered, most of these marine-indicating specimens were found as disarticulated valves, suggesting they had been transported into the Bay from the oceanic realm after death.

Rare occurrences of the introduced species *Eusarsiella zostericola* were also found in South Bay at the SFEI sites of San Bruno Shoal, Dumbarton Bridge, and South Bay. This species was introduced into San Francisco Bay with the oyster *Crassostrea virginica* Gmelin, which was transplanted from the Atlantic Coast in 1869 (Kornicker, 1975). Although the first oyster beds cultivated in San Francisco Bay were located in Central Bay, they were soon abandoned and by 1875, all of the beds were situated in South Bay instead (Skinner, 1962). They remained there until about 1900 when the oysters being grown were unfit for market due to sewage and traffic on the Bay, forcing the industry to move to Humboldt Bay and other locations (Skinner, 1962). Obviously,

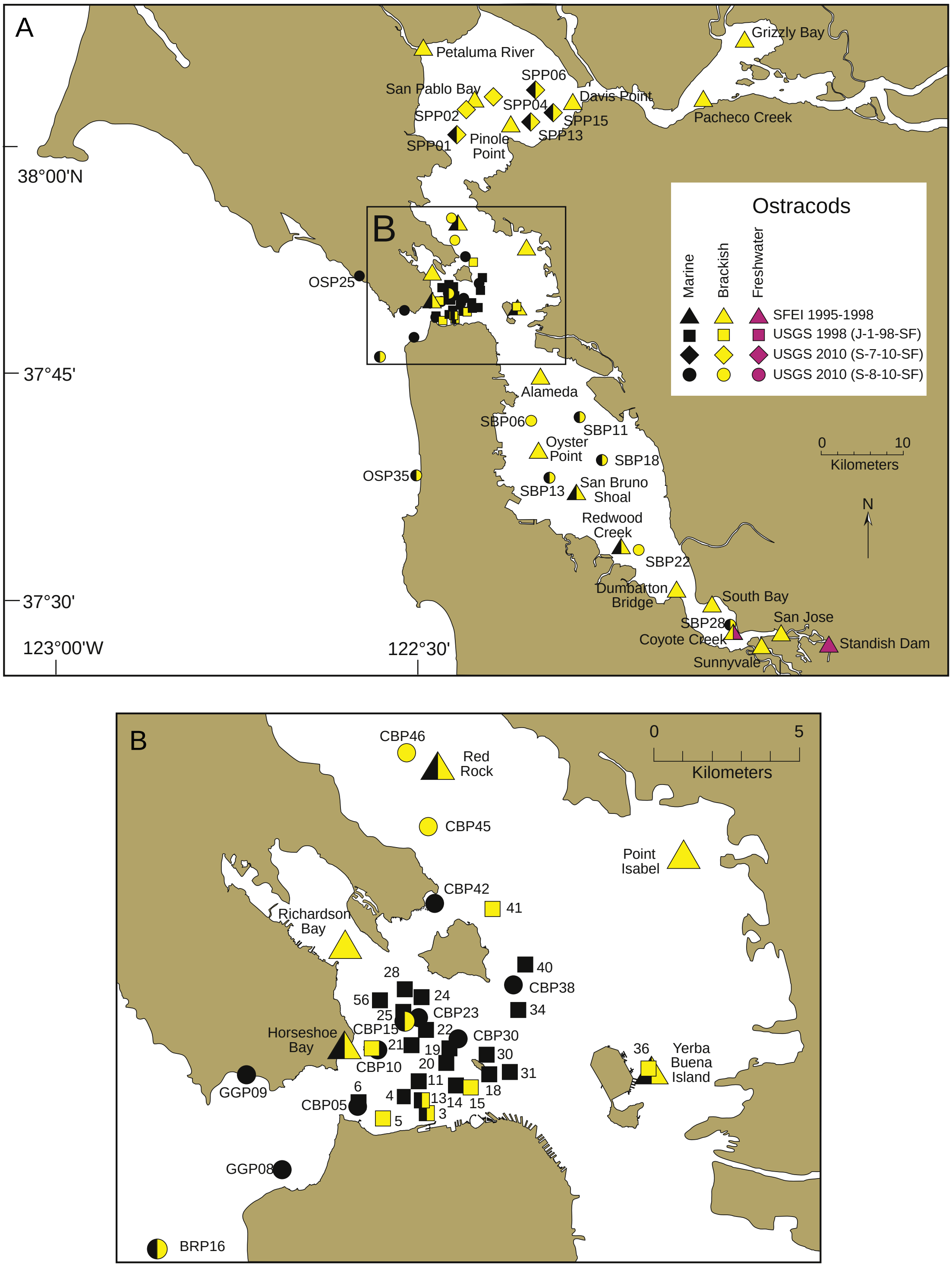


Fig. 15. Spatial distribution of marine, brackish, and freshwater ostracods at the 1995–2010 San Francisco Bay Coastal System stations. B. Detailed map of the stations in Central Bay, the Golden Gate, and the eastern portion of the San Francisco Bar. Bicolored symbols represent stations where two constituents are present.

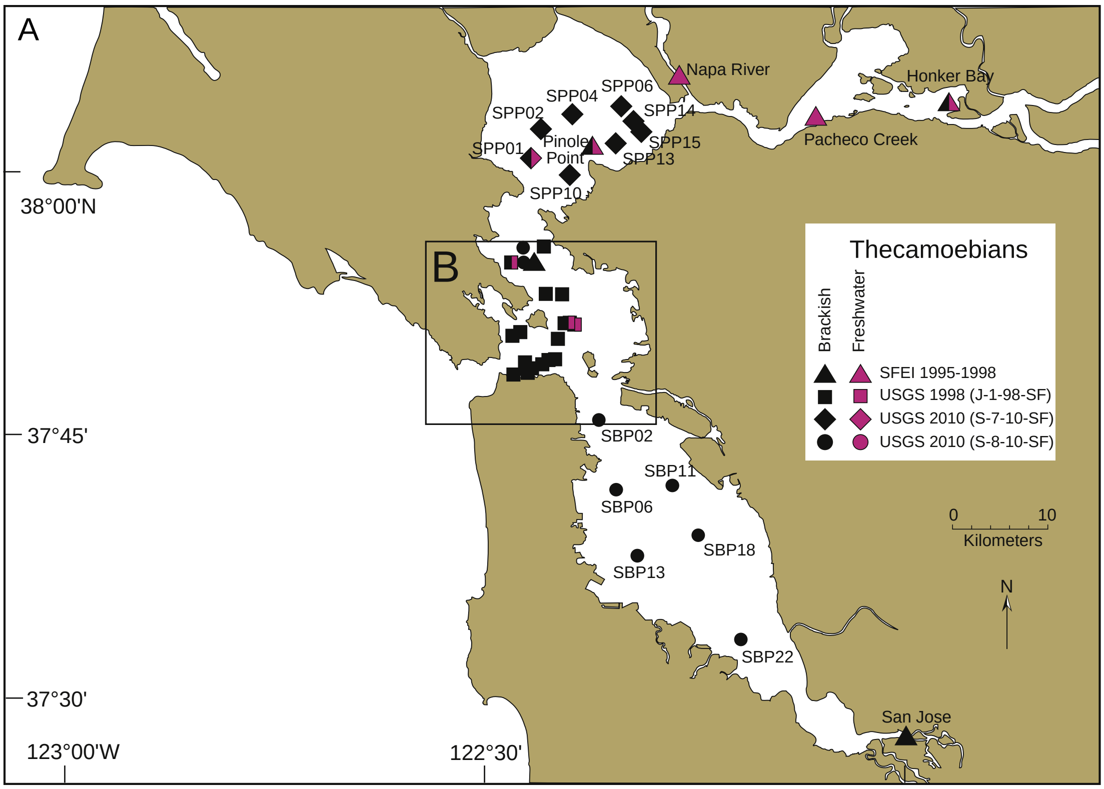
E. zostericola adapted to the brackish environment in which it was introduced, as it is still found in South Bay today. However, it is surprising that this species has not spread to the other brackish areas of San Francisco Bay, including Richardson Bay, the eastern portion of Central Bay, and San Pablo Bay. It is possible that the nearly-marine waters of Central Bay act as a barrier to its dispersal to the other brackish areas of the Bay, or that the species cannot survive the saline (~30 psu) conditions in the channel of South Bay that acts as a conduit for transport of water and sediment between South Bay and the remaining portions of San Francisco Bay.

A few specimens of *Ilyocypris gibba*, a freshwater species (Smith and Delorme, 2010), were recovered at the South Bay SFEI sites of Standish Dam and Coyote Creek (Fig. 15). The salinity at the Standish Dam site was 0 psu when the sample was collected in August 1997 (Appendix 1) so the recovery of a freshwater species is to be expected. In contrast, the salinity at the Coyote Creek site was 10 psu in February

1998, which suggests the freshwater taxon was transported a short distance out to this brackish-water site in South Bay.

7.6. Thecamoebians

These tiny organisms are related to foraminifera but differ from them in that most live and reproduce in freshwater benthic environments, surviving only temporary exposures to brackish water by means of encystment; only a few live in oligohaline environments to ~5 psu (Scott et al., 2001). A single species of these freshwater thecamoebians, *Arcella vulgaris* Ehrenberg, was recovered at eight sites in San Francisco Bay: in North Bay at SPP01 and the SFEI sites of Honker Bay, Pacheco Creek, Napa River, and Pinole Point, as well as in Central Bay at sites 37, 38, and 50 (Fig. 16). The species is known to be tolerant of sediment moderately to heavily contaminated by arsenic, mercury, and silver (Patterson et al., 1996; Scott et al., 2001). There are also only two forms of thecamoebians that are capable of reproducing in predominantly brackish environments, both of which were recovered in this study: *Centropyxis* spp. and *Difflugia oblonga* Ehrenberg (Scott et al., 2001; Patterson and Kumar, 2002). The species that was most abundant



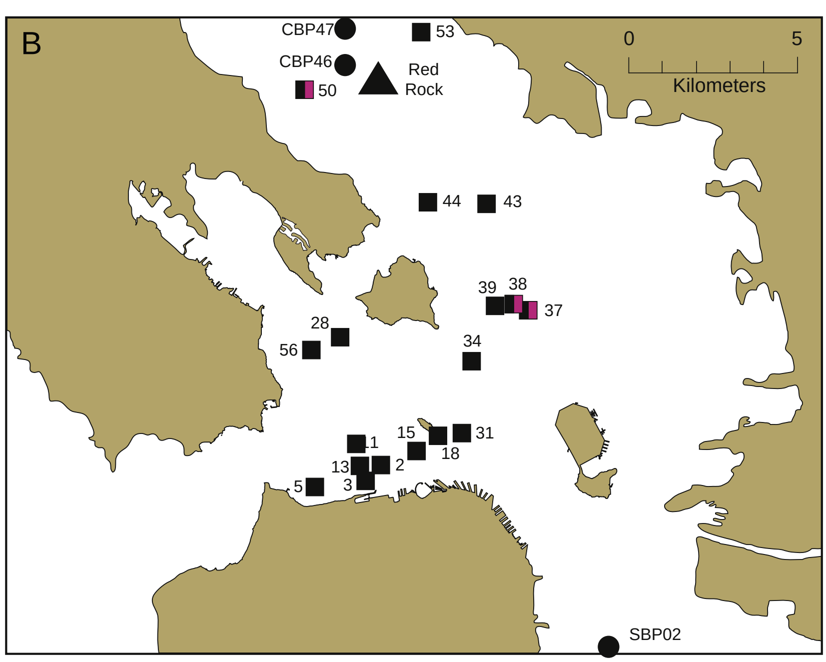


Fig. 16. Spatial distribution of brackish and freshwater thecamoebians at the 1995–2010 San Francisco Bay Coastal System stations. B. Detailed map of the stations in Central Bay, the Golden Gate, and the eastern portion of the San Francisco Bar. Bicolored symbols represent stations where both constituents are present.

and occurred throughout San Francisco Bay was *Centropyxis constricta* (Ehrenberg); *Centropyxis aculeata* Ehrenberg and *D. oblonga* were each found only once, at sites 38 and 51, respectively, in Central Bay. *Centropyxis constricta* is often found dominating estuarine regions with salinities <5‰ and pH < 6.2. *Centropyxis aculeata* is also tolerant of these same conditions (Patterson et al., 1985), whereas *D. oblonga* is known to live in acidic environments (pH < 6.2) (Ellison, 1995; Scott et al., 2001).

Estuaries are commonly characterized by a substantial amount of reworking of thecamoebian tests, which are often distributed discontinuously (Bartlett, 1966; Scott et al., 2001). In this study, thecamoebians representing both freshwater and marginally brackish (salinity <5‰) environments were recovered. The freshwater specimens (*Arcella vulgaris*) most likely were transported into San Francisco Bay from several of the nearly 300 rivers, creeks, and sloughs that form a dense and widespread network of watercourses feeding into the Bay (List of Watercourses in the San Francisco Bay Area, 2012; San Francisco Bay Area Creek and Watershed Finder, 2012). The marginal brackish taxa (*Centropyxis aculeata*, *Centropyxis constricta*, and *Difflugia oblonga*) probably originated in the marshes and mudflats that line the perimeter of the Bay in many regions, environments characterized by low salinities (<5‰) and acidic conditions (pH < 6.2). Both the freshwater and marginal brackish water thecamoebians recovered in sediment samples from the centers of San Pablo Bay and Central and South Bays (Fig. 16) do not live in those environments and must have been transported to those locations by the currents in San Francisco Bay.

7.7. Macrofauna

Although a diverse macrofaunal assemblage was recovered in this study (Appendix 8), most of the taxa reside in both coastal and estuarine environments, thereby providing little information on sediment transport in the San Francisco Bay Coastal System. The exceptions are the bivalve mollusk *Ostrea* sp. and the gastropod *Rictaxis punctocaelatus*, which are restricted to bays, the introduced Asian bivalve *Theora lubrica*, which lives in mud of protective bays (Coan et al., 2000), and the questionably identified Planorbidae gastropod, which lives in freshwater.

7.8. Macroflora

Seeds are the most frequently encountered plant remains in the sediments of San Francisco Bay. Among them, bulrush (tule; *Scirpus* spp.) are the most common and geographically widespread, being recovered in San Pablo Bay, and South and Central Bays. *Scirpus* seeds were also recovered in late Pleistocene and Holocene deposits under South Bay (Atwater et al., 1979; Sloan, 1992). In the present San Francisco Bay, the taxon is a dominant plant in the fresh and brackish marshes (Atwater et al., 1979; Ustin et al., 1982).

7.9. Volcanic ash

Volcanic glass shards were recovered throughout the Bay and out into the offshore region (Fig. 11). Electron microprobe analyses indicate that the chemical compositions of each of the five analyzed volcanic glass samples are highly polymodal (mean: three subpopulations), with reworked shards that chemically correlate to multiple eruptive source areas such as the southern Cascades (e.g., the Nomlaki Tuff from the Mount Lassen area), the Sonoma and Mono-Inyo Craters volcanic fields, and sedimentary units in the Great Valley region of California (Appendix 9). These range from Miocene (most likely 19–23 Ma) to Pliocene (3.27 Ma) in age (Woloszyn, 1979; Bartow, 1994; Wahrhaftig, 2000; Poletski, 2010). None of the volcanic ash correlatives outcrop locally. The weathered, sub-rounded to rounded pumiceous shard morphology, and the heterogeneous geochemical fingerprints of each of the five analyzed glass samples, along with correlations to volcanic ash beds at distal

Table 2
Key sediment constituents representative of the source areas recognized in the San Francisco Bay Coastal System.

		Source area				
		Freshwater	Brackish/estuarine	Marine	Terrestrial	Volcanic
Key sediment constituent	Anthropogenic				Glass microsphere Welding slag	
	Bivalve mollusk		*Ostrea* sp. *Theora lubrica*			
	Benthic foraminifera		*Ammonia tepida* *Elphidiella hannai* *Elphidium excavatum* *Entzia tetrastomella* *Haplophragmoides subinvolutum* *Haynesina germanica* *Miliammina fusca* *Trochammina hadai* *Trochammina inflata*	*Buccella tenerrima* *Buliminella elegantissima* *Cassidulina limbata* *Cibicides fletcheri* *Elphidium frigidum* *Rotorbinella campanulata* *Trichohyalus ornatissima* *Trochammina pacifica*		
	Diatom	*Cymbella* sp.		*Isthmia nervosa* *Triceratium* sp.		
	Fossil (recrystallized)				Planktic foraminifera Radiolarian	
	Gastropod	Planorbidae?	*Rictaxis punctocaelatus*	*Scabrotrophon*? sp. *Turbonilla*? sp.		
	Ostracod	*Ilyocypris gibba*	*Cyprideis beaconensis* *Eusarsiella zostericola* *Physocypria globula* *Spinilebris hyalina*	*Ambostracon* sp. *Aurila lincolnensis* *Cytheromorpha grandwashensis* *Hemicythere hazeli* *Radimella aurita* *Robustaurila jollaensis*		
	Planktic foraminifera Radiolarian			Planktic foraminifera Radiolarian		
	Thecamoebian	*Arcella vulgaris*	*Centropyxis constricta*			
	Volcanic Glass (Tuff)					Nomlaki Valley Springs Formation Great Valley

rather than proximal sites, suggest a high degree of transport before redeposition in San Francisco Bay.

7.10. Sediment dynamics

The primary sediment transport mechanisms impacting the San Francisco Bay Coastal System are the Sacramento and San Joaquin Rivers in the northeast and oceanic water from the west through the Golden Gate. Although local creeks and sloughs that drain into the Bay are numerous (San Francisco Bay Area Creek and Watershed Finder, 2012), they are generally only of significance seasonally. By documenting the spatial distribution of naturally-situated and allochthonous sedimentological constituents throughout the Bay and offshore, we can identify pathways of sediment transport within the San Francisco Bay Coastal System.

Five source areas were encountered in this study, namely freshwater, brackish/estuarine, marine, terrestrial, and volcanic, and each is characterized by a unique group of representative ("key") constituents. The constituents that proved to be most useful in identifying these source areas, and their distribution in the San Francisco Bay Coastal System, are presented on Tables 2 and 3, respectively.

Constituents of the freshwater source area (i.e., ostracod *Ilyocypris gibba*, diatom *Cymbella* sp., thecamoebian *Arcella vulgaris*, and a questionable Planorbidae gastropod) were recovered throughout the San Francisco Bay Coastal System except for the San Francisco Bar (Figs. 15, 16). The transport mechanism of these faunal elements could have been any of the creeks and sloughs which feed directly into the estuary or marine realm, or into the Sacramento and San Joaquin Rivers. In most cases they are found near the edges of the estuary (Honker Bay, Pacheco Creek, extreme South Bay) and inland at Standish Dam; that is, not far from their original sources. Occasionally, however, they were also transported some distance to the middle of San Pablo Bay and Central Bay, or out past the Golden Gate to the offshore region.

The brackish/estuarine source area is characterized by a far more diverse faunal array: the thecamoebian *Centropyxis constricta*, the gastropod *Rictaxis puntocaelatus*, the ostracods *Cyprideis beaconensis*, *Eusarsiella zostericola*, *Physocypria globula*, and *Spinilebris hyalina*, the bivalve mollusks *Ostrea* sp. and *Theora lubrica*, and benthic foraminifera of both the Brackish Shallow Subtidal Biofacies (*Entzia tetrastomella*, *Haplophragmoides subinvolutum*, and *Miliammina fusca*) and the Estuarine Shallow Subtidal Biofacies (*Ammonia tepida*, *Elphidiella hannai*, *Elphidium excavatum*, *Haynesina germanica*, *Trochammina hadai*, and *Trochammina inflata*). The presence of most of these faunal constituents in San Francisco Bay is expected. However, thecamoebians and benthic foraminifera that normally dwell in brackish environments were recovered in the center of the Bay and estuarine-dwelling forms were found westward of the Golden Gate, out on the San Francisco Bar, and offshore (Figs. 12, 16). These occurrences are considered allochthonous and attributed to sediment transport.

Faunal elements of the marine source area were recovered throughout the coastal system (Figs. 12, 14, 15). Representatives of this source area are radiolarians, planktic foraminifera, the diatoms *Isthmia nervosa* and *Triceratium* sp., the gastropods *Scabrotrophon*? sp. and *Turbonilla*? sp., the ostracods *Ambostracon* sp., *Aurila lincolnensis*, *Cytheromorpha grandwashensis*, *Hemicythere hazeli*, *Radimella aurita*, and *Robustaurila jollaensis*, and the benthic foraminifera *Buccella tenerrima*, *Buliminella*

Table 3
Spatial distribution of the key sediment constituents and the source areas they represent in the San Francisco Bay Coastal System.

			San Francisco Bay Coastal System regions						
		Constituent	Suisun, Grizzly, and Honker Bays	San Pablo Bay	South Bay	Central Bay	Golden Gate	San Francisco Bar	Offshore
Source area	Freshwater	Diatom	X						
		Gastropod	X	X	X	X	X		X
		Ostracod			X				
		Thecamoebian	X	X		X			
	Brackish/estuarine	Benthic foraminifera	X	X	X	X	X	X	X
		Bivalve mollusk		X	X				
		Gastropod			X				
		Ostracod	X	X	X	X		X	X
		Thecamoebian	X	X	X	X			
	Marine	Benthic foraminifera		X	X	X	X	X	X
		Diatom	X	X	X	X		X	X
		Gastropod			X		X		
		Ostracod		X	X	X		X	X
		Planktic foraminifera		X	X	X			
		Radiolarian		X	X	X			X
	Introduced	Benthic foraminifera	X	X	X	X	X	X	X
		Bivalve mollusk		X	X				
		Ostracod			X				
	Terrestrial	Glass microsphere	X	X	X	X		X	X
		Recrystallized foraminifera	X	X	X	X			X
		Recrystallized radiolarian	X						X
		Welding slag		X	X	X		X	
	Volcanic	Glass shard	X	X	X	X	X	X	X
	indeterminate	Bryozoan	X	X		X	X	X	X
		Crab claw			X	X			X
		Echinoid spine		X	X	X	X	X	X
		Fish element	X	X	X	X	X	X	X
		Gastropod operculum			X	X			
		Scirpus seed		X	X	X			
		Seed (other)	X	X	X	X			
		Spore	X	X		X			
		Worm tube		X		X			
Benthic foraminiferal biofacies	Brackish shallow subtidal		X	X	X	X			
	Estuarine shallow subtidal			X	X	X		X	
	Estuarine intermediate/deep subtidal				X	X		X	
	Nearshore marine					X	X	X	X

elegantissima, *Cassidulina limbata*, *Cibicides fletcheri*, *Elphidium frigidum*, *Rotorbinella campanulata*, *Trichohyalus ornatissima*, and *Trochammina pacifica*.

The occurrence of only rare living specimens of the Nearshore Marine Foraminiferal Biofacies in Central Bay suggests that the foraminifera are allochthonous there and that the currents are responsible for carrying sediment and the associated biota back and forth through the Golden Gate. The recovery of additional marine elements in San Pablo Bay suggests incursions from the Pacific Ocean commonly extend about one-half to two-thirds up the Bay towards the Carquinez Strait and occasionally as far as Pacheco Creek, Honker Bay, and Grizzly Bay. Similarly in South Bay, the presence of allochthonous marine faunal elements (Arnal et al., 1980; this study) and of highly saline water in the summer (Fig. 4A, C, E) and in the channels nearly all year round except in rare low-flow years (U.S. Geological Survey Water Resources Division San Francisco Bay Water Quality, 2012), suggests marine incursions are common, even south of the Dumbarton Bridge. The transport of sediment constituents is further suggested by the presence of all four foraminiferal benthic foraminiferal biofacies in the shallow (<3 m) eastern margin of South Bay, with a considerably lower percentage of stained (i.e., living) foraminiferal tests compared to other South Bay sites. The benthic foraminiferal fauna here also has a higher number of species (22 versus approximately 12), and substantially more abundant specimens (i.e., BF# = 1165 and 527 at SBP11 and SBP18, respectively), than others encountered in this study. In contrast, samples recovered away from the margins of the Bay toward the deep channel are characterized by progressively fewer benthic foraminifera and less diversity, with the channel sites having the least foraminifera of all. Like the channel in the San Pablo Bay, the scarcity of constituents recovered in this channel implies this is a site of sediment winnowing.

Sediment constituents from the terrestrial realm are glass microspheres from road striping, welding slag possibly from boat repairs in docks, and recrystallized (fossilized) foraminifera and radiolarians assumed to come from the erosion of land-based outcrops. Most of these elements were recovered from the margins of the estuary (Fig. 10) with the input thought to be derived from local watercourses as well as the Sacramento and San Joaquin Rivers. However, there are also many examples where they were found in the middle of South and Central Bays that are clearly the result of sediment transport.

Volcanic glass was widely distributed in the San Francisco Bay Coastal System (Fig. 11). Because reworked and heterogeneous volcanic shards of mixed tephra (Nomlaki, Valley Springs, and Great Valley Formation) were recovered at several sites over a substantial area of the Bay (i.e., San Pablo Bay to the Golden Gate) and no local volcanic outcrops are known, we assume the tephra throughout the Bay is fluvially transported from these distant volcanic eruptive source areas in the Great Valley, California. The Sacramento and San Joaquin Rivers are the primary transport mechanism of sediment carrying tephra from its origin, through the delta, and into the Bay. The tephra is then transported throughout each of the subembayments, as well as out the Bay, onto the San Francisco Bar, and into the nearby offshore region primarily south, but also north, of the Golden Gate.

Synthesizing these distributional patterns allows us to infer what the sediment transport pathways are in the San Francisco Bay Coastal System (Fig. 17). The occurrence of heterogeneous volcanic shards suggests sediment is transported from central California, through the Delta to all subembayments of the Bay, and to the oceanic realm offshore. The presence of allochthonous estuarine benthic foraminifera outside the Bay on the San Francisco Bar also demonstrates that sediment is, at times, moving to the west out of the Bay. Once outside, the majority of the sediment moves to the south, although the presence of both estuarine benthic foraminifera and tephra at stations to the north of the Bay suggest there is either a small component of northward transport as well or some input to the littoral drift from another estuarine source to the north (e.g., Bolinas Lagoon where Hedman (1975) reported recovering estuarine foraminifera, or possibly Drakes Estero)

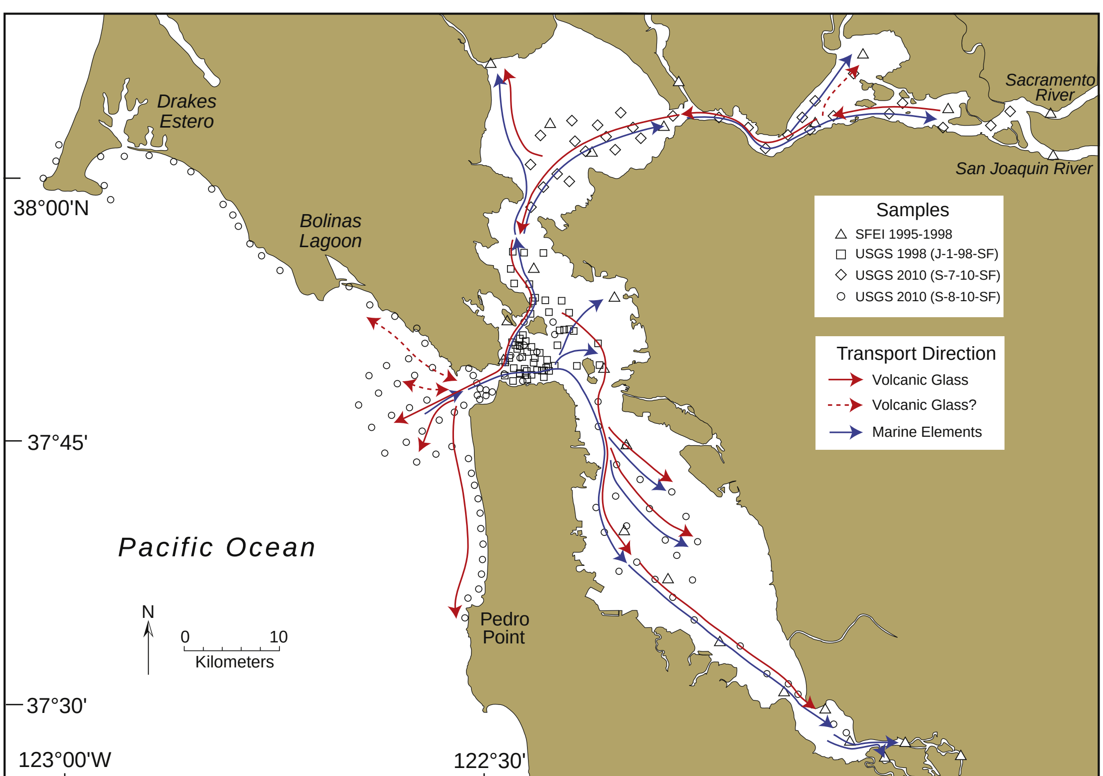


Fig. 17. Inferred sand transport pathways in the San Francisco Bay Coastal System based on the presence of allochthonous marine biologic and terrestrial volcanic sediment constituents. Possible transport pathways of anthropogenic and biologic sediment constituents from the terrestrial realm to the center of the subembayments not shown due to uncertainty of source area and space limitations.

that is carried to the south towards San Francisco Bay. In contrast, marine biologic elements (radiolarians, diatoms, ostracods, gastropods, and benthic and planktic foraminifera) are transported by the flood tide in the opposite direction, through the Golden Gate into Central Bay, San Pablo Bay, and South Bay. Occasionally, sediment will be transported as far north as Grizzly and Honker Bays and the extreme southern end of South Bay. Finally, the presence of allochthonous freshwater (ostracods, thecamoebians, gastropods, and diatoms) and terrestrial (welding slag, glass microspheres, and fossilized microorganisms) elements in the middle of Central and South Bays suggests sediment is transported by local and regional watercourses away from terrestrial and marginal estuarine regions.

Based on nine provenance techniques (i.e., grain size morphometrics, strontium/neodymium isotopic ratios, rare earth element composition, heavy minerals, semi-quantitative X-ray diffraction, bedform asymmetry, sediment constituents, acoustic Doppler velocity measurements, and numerical modeling), Barnard et al. (2013–in this issue-a) produced a conceptual model of the primary beach-sized sand transport pathways in the San Francisco Bay Coastal System. These pathways are in good agreement with those suggested by the biologic, anthropogenic, and volcanic constituents used in this study. The minor discrepancies include the possible small northward component outside the Bay and the occasional transport of marine elements as far as Grizzly and Honker Bays and the southern portion of South Bay. These discrepancies in transport direction may reflect the fact that there are differences in the hydraulic properties of the material studied (e.g., foraminifera versus mineral grains), or that only the primary pathways were considered in the conceptual model, whereas primary and secondary transport pathways were identified by the distribution of the sediment constituents.

8. Conclusions

The biological, anthropogenic, and volcanic constituents of 332 samples collected in San Francisco Bay and the nearby coastal area from 1995 to 2010 were analyzed to discern patterns of sediment transport in the region. The biological constituents investigated include microfauna, macrofauna, and flora, and the anthropogenic objects are welding slag and glass microspheres most likely used to increase road reflectivity. The volcanic constituents are volcanic glass shards of the Miocene portion (most likely 19–23 Ma) of the Valley Springs Formation and Great Valley tephras, and the Pliocene (3.27 Ma) Nomlaki Tuff Member of the Tuscan Formation, all of which originate in the Great Valley, California.

The census data of one microfaunal group (the benthic foraminifera) was further refined by R- and Q-mode cluster analysis to more clearly define their distributional pattern. Six taxonomic associations (TA1–6) and four station clusters (SC1–4) were identified. Similar results of the R- and Q-mode cluster analyses allow us to define four benthic foraminiferal biofacies: Brackish Shallow Subtidal, Estuarine Shallow Subtidal, Estuarine Intermediate/Deep Subtidal, and Nearshore Marine. A Principal Components Analysis of the local environmental factors (water depth, pH, %TOC, bottom water temperature, bottom water salinity, dissolved oxygen, and grain size) and associated foraminiferal census data suggests decreasing grain size varies with increasing sediment carbon, dissolved oxygen varies inversely with water temperature and salinity, and the biofacies reflect these environmental parameters as well as sediment transport.

The distribution of sediment constituents found in the San Francisco Bay Coastal System is a valuable proxy for sediment transport in the region. Sediment containing tephra is fluvially transported from the Sacramento–San Joaquin Delta to all regions of the Bay and out into the offshore realm. Marine-dwelling benthic and planktic foraminifera, ostracods, diatoms, and radiolarians are carried from offshore into the Bay, occasionally transported as far north as Honker Bay and the southern end of South Bay. Additionally, terrestrial (welding slag and glass microspheres) and freshwater (gastropods and ostracods) to marginal estuarine (thecamoebians and marsh-indicating benthic foraminifera) constituents are found in the middle of the subembayments, far from their points of origin. Although the channel in North, Central, and South Bays, and the Golden Gate, are the main conduits for sediment movement and sites where scouring occurs, smaller local watercourses are also seasonally significant. A similar multi-proxy sediment constituent approach can be applied to the investigation of sediment transport pathways in other coastal systems worldwide.

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Exhibit H

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A Sr–Nd isotopic study of sand-sized sediment provenance and transport for the San Francisco Bay coastal system

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ABSTRACT

A diverse suite of geochemical tracers, including $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope ratios, the rare earth elements (REEs), and select trace elements were used to determine sand-sized sediment provenance and transport pathways within the San Francisco Bay coastal system. This study complements a large interdisciplinary effort (Barnard et al., 2012) that seeks to better understand recent geomorphic change in a highly urbanized and dynamic estuarine-coastal setting. Sand-sized sediment provenance in this geologically complex system is important to estuarine resource managers and was assessed by examining the geographic distribution of this suite of geochemical tracers from the primary sources (fluvial and rock) throughout the bay, adjacent coast, and beaches. Due to their intrinsic geochemical nature, $^{143}Nd/^{144}Nd$ isotopic ratios provide the most resolved picture of where sediment in this system is likely sourced and how it moves through this estuarine system into the Pacific Ocean. For example, Nd isotopes confirm that the predominant source of sand-sized sediment to Suisun Bay, San Pablo Bay, and Central Bay is the Sierra Nevada Batholith via the Sacramento River, with lesser contributions from the Napa and San Joaquin Rivers. Isotopic ratios also reveal hot-spots of local sediment accumulation, such as the basalt and chert deposits around the Golden Gate Bridge and the high magnetite deposits of Ocean Beach. Sand-sized sediment that exits San Francisco Bay accumulates on the ebb-tidal delta and is in part conveyed southward by long-shore currents. Broadly, the geochemical tracers reveal a complex story of multiple sediment sources, dynamic intra-bay sediment mixing and reworking, and eventual dilution and transport by energetic marine processes. Combined geochemical results provide information on sediment movement into and through San Francisco Bay and further our understanding of how sustained anthropogenic activities which limit sediment inputs to the system (e.g., dike and dam construction) as well as those which directly remove sediments from within the Bay, such as aggregate mining and dredging, can have long-lasting effects.

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1. Introduction

The San Francisco Bay coastal system is bounded to the east by the mouths of the Sacramento–San Joaquin Rivers and to the west by the Pacific Ocean, and is one of the largest, most heavily impacted, and best studied (e.g. Conomos, 1979; Nichols et al., 1986; Cloern, 2001; Cloern and Jassby, 2012) estuarine systems in the western United States. The 163,000 km^2 watershed (~40% of the area of California) encompasses parts of the Sierra Nevada Mountains, the Coastal Range, and the Central Valley, and about 40% of the annual runoff is produced from spring snowmelt. During the late 1800s, pervasive hydraulic mining, land clearing and logging steadily increased sediment inflow to the bay (Gilbert, 1917; Ingram and DePaolo, 1993), while in the 1900s water diversions and the construction of dams dramatically decreased sediment inflows (Van Geen et al., 1999; Schoellhamer, 2009). Today, sediment yields from the Sacramento River are estimated to be about seven times that of the San Joaquin River (Oltmann et al., 1999; Wright and Schoellhamer, 2005). Historically, the majority of sediment entering the Bay was through the Sacramento–San Joaquin Delta; however recent estimates suggest that local tributaries may now be playing a larger role in suspended sediment delivery (McKee et al., 2013-this issue). The suspended sediment loads discharging into the Bay carry a unique geochemical signature of the weathered source rocks (Murray et al., 1990), as well as some imprint of human activity, such as mining, agriculture, and industry (Marvin-DiPasquale et al., 2003; Bouse et al., 2010). Inflowing sediment is likely to undergo further chemical and physical alteration during transport to the sea (Taylor and McLennan, 1985, 1995; Stordal and Wasserburg, 1986; Piepgras and Wasserburg, 1987; Grousset et al., 1988; Banner, 2004; Wei et al., 2012). Understanding the primary sources of sediment and transport pathways throughout this heavily urbanized system will enable more informed management of coastal resources. To utilize a natural geochemical tracer for sand-sized sediment movement in San Francisco Bay, the tracer should ideally be able to discriminate dominant source materials from background, should be chemically inert during transport and deposition such that these processes cannot readily alter or erase the parent material signature, and should be easily and reliably measurable.

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Unfortunately, the geochemical behavior of many isotopes and trace elements very rarely exhibit all of three characteristics and as a consequence it is often necessary to use several distinct tracers in concert.

Of the isotopes generally used to track sediment movement, neodymium ($^{143}Nd/^{144}Nd$) isotopes are particularly useful because sediment generally retains its Nd isotopic signature throughout weathering, transport, deposition, and diagenesis (DePaolo, 1981; Goldstein et al., 1984; Linn et al., 1992; Jones et al., 1994; Winter et al., 1997). Strontium isotopes ($^{87}Sr/^{86}Sr$) are similarly promising provenance tracers (Faure, 1986; Hemming et al., 2007; Wei et al., 2012), although Sr isotopes have the added complexity of being affected by mixing with seawater that has high concentrations of marine Sr. Rare earth elements (REE) offer a systematic, complimentary perspective on weathering and transport (Nesbitt et al., 1980; Sholkovitz, 1995; Mazumdar et al., 2003) because REE variations in marine sediment can be directly attributable to the depositional environment (Stordal and Wasserburg, 1986; Piepgras and Wasserburg, 1987). Rivers are the principal source of REE to the oceans and while riverine REE signatures do not exhibit pronounced fractionation of Ce from other REE, in oxic seawater oxidation of Ce(III) to insoluble Ce(IV), predominantly on manganese oxides, causes the preferential removal of Ce from the water column — the so called Ce anomaly (Sholkovitz, 1995). Specifically, criteria based on the Ce anomaly or variations in total REE abundances (ΣREE) allow for the discrimination of depositional environments (Cullers and Graf, 1983) that may otherwise be physically indistinct (e.g., chert). Perhaps the least useful of the geochemical proxies are trace elements and their ratios (e.g., Zr/Hf, Th/U, Ca/V), which are relatively easy to quantify using modern mass spectrometry, and sometimes do provide additional information on sediment source material, anthropogenic perturbations, and sediment provenance.

In this paper, we employ $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios, REE, and select trace elements in the source materials (rocks and fluvial sand) and surface sediment from the bay/seafloor as well as beaches to examine sediment transport and provenance of sand in the San Francisco Bay coastal system. Results confirm that most sediment flowing into this system is derived from the Sierra Nevada Batholith via the Sacramento River, with lesser contributions from the Napa and San Joaquin Rivers. Isotopic signatures also reveal local sediment sources and sediment depot-centers. Such data are used to estimate sand-sized sediment transport pathways and provenance.

2. Study area

The rocks of the San Francisco Bay region consist of complex assemblages of bedrock and surficial deposits that differ vastly in lithology, age, and thickness (Fig. 1). Bedrock consists of Jurassic and Cretaceous rocks of the Franciscan Complex and granitic rocks of the Salinian block. The unconsolidated surficial deposits are Pleistocene and Holocene sands, mud, and clay, as well as extensive alluvium and landslide debris. In the San Francisco Bay watershed, the Franciscan Complex may be more than 3000-m thick and is host to one of the greatest

Fig. 1. Physiographic map of San Francisco Bay coastal system (modified from Graymer et al., 2006), showing geochemical sampling locations. Dashed lines denote regional divisions described in the text. GG = Golden Gate; PL = Pt. Lobos; PB = Pt. Bonita; AI = Angel Is. Locations of Russian, Napa, Sacramento, and San Joaquin River samples are shown in Fig. 2.

Table 1
Latitude, longitude, Sr–Nd[a] isotopic ratios and εNd[a], sorted by region and sample type.

Sample ID	Longitude (dec. degrees)	Latitude (dec. degrees)	$^{87}Sr/^{86}Sr$ ($+/- 2\sigma \times 10^6$)	$^{143}Nd/^{144}Nd$ ($+/- 2\sigma \times 10^6$)	εNd
North Bay					
Sacramento River					
Sac R. — north (SAC01)	−121.51916	38.56280	0.705138 (9)	0.512595 (8)	−0.80
Sac R. — mid (SACFP)	−121.50161	38.45381	0.705203 (7)	0.512587 (10)	−0.95
Sac R. — south (SACHD)	−121.52169	38.36947	0.705451 (8)	0.512542 (8)	−1.84
San Joaquin River					
San Joaquin R. — south (SJC02)	−121.30836	37.78738	0.706599 (8)	0.512376 (6)	−5.06
San Joaquin R. — north (SJRST)	−121.32964	37.93486	0.706896 (8)	0.512386 (6)	−4.88
North Bay Tributaries					
Wildcat Crk. (CR_01)	−122.319	37.952	0.707303 (7)	0.512478 (5)	−3.08
Napa R. (CR_03)	−122.395	38.441	0.706924 (8)	0.512563 (7)	−1.42
Sonoma Crk. (CR_04)	−122.467	38.266	0.705383 (8)	0.512777 (7)	2.75
North Bay Beaches					
Pinole (SFPBCH11)	−122.29700	38.01440	0.705764 (7)	0.512559 (7)	−1.50
North Bay Offshore					
SSP01	−122.20863	38.06013	0.705579 (7)	0.512543 (7)	−1.81
SSP04	−122.12530	38.04237	0.705658 (8)	0.512539 (7)	−1.88
SSP07	−122.07089	38.09251	0.705666 (8)	0.512623 (8)	−0.25
SSP11	−122.03528	38.06494	0.705597 (8)	0.512590 (7)	−0.89
SSP17	−121.90838	38.04551	0.705760 (7)	0.512570 (7)	−1.28
SPP07	−122.43677	37.97509	0.705657 (9)	0.512535 (8)	−1.98
SPP12	−122.34540	38.04189	0.705562 (8)	0.512564 (8)	−1.40
SPP16	−122.26445	38.06178	0.705841 (7)	0.512509 (10)	−2.47
South Bay					
South Bay Tributaries					
San Francisquito Crk. (CR_08)	−122.191	37.445	0.709098 (7)	0.512414 (6)	−4.32
Guadalupe R. (CR_09)	−121.938	37.380	0.707543 (8)	0.512498 (7)	−2.69
Alameda Crk. (CR_10)	−121.969	37.578	0.707024 (7)	0.512482 (9)	−3.00
Calaveras Crk. (CR_11A1)	−121.865	37.569	0.707489 (8)	0.512461 (8)	−3.41
South Bay Offshore					
SBP02	−122.35823	37.76467	0.706376 (7)	0.512445 (8)	−3.73
SBP06	−122.33806	37.69822	0.707543 (8)	0.512498 (7)	−2.70
SBP13	−122.31331	37.63531	0.707669 (9)	0.512443 (7)	−3.76
Golden Gate and Bar					
Golden Gate and Bar Source Rocks					
Basalt — Pt. Bonita (SFPCLF02A)	−122.53033	37.82010	0.704841 (8)	0.512953 (6)	6.19
Serpentinite — Fort Pt. (SFPCLF04)	−122.47866	37.80197	0.707447 (10)	–	–
Sandstone — Pt. Lobos (SFPCLF13_14) [b]	−122.51412	37.78132	0.710633 (9)	0.512234 (6)	−7.84
Golden Gate and Bar Beaches					
Baker Bch (SFPBCH20)	−122.48426	37.79277	0.706029 (7)	0.512406 (5)	−4.48
Bonita Cove (SFPBCH33)	−122.50904	37.82439	0.706044 (10)	0.512760 (9)	2.41
Kirby Cove (SFPBCH34)	−122.48957	37.82685	0.709991 (8)	0.512476 (7)	−3.12
Golden Gate and Bar Offshore					
GGP01	−122.51949	37.78569	0.706104 (7)	0.512547 (8)	−1.74
GGP03	−122.51949	37.80571	0.706044 (8)	0.512508 (8)	−2.50
GGP09	−122.51332	37.82087	0.706089 (8)	0.512556 (8)	−1.56
GGP12	−122.49983	37.80136	0.706113 (7)	0.512506 (9)	−2.53
GGP15	−122.48536	37.79812	0.706298 (7)	0.512548 (6)	−1.71
BRP02	−122.61207	37.82373	0.706090 (7)	0.512504 (9)	−2.57
BRP04	−122.64585	37.78638	0.706059 (6)	0.512455 (9)	−3.52
BRP06	−122.59936	37.80654	0.706197 (8)	0.512509 (9)	−2.48
BRP08	−122.55707	37.82163	0.706044 (7)	0.512397 (9)	−4.66
BRP10	−122.60646	37.77638	0.706299 (10)	0.512451 (9)	−3.62
BRP14	−122.58888	37.75078	0.706000 (7)	0.512473 (7)	−3.17
BRP16	−122.54905	37.77161	0.706445 (9)	0.512521 (7)	−2.25
BRP18	−122.57645	37.73173	0.706052 (8)	0.512503 (7)	−2.59
BRP19	−122.55322	37.73924	0.706063 (10)	0.512534 (9)	−1.99
Central Bay					
Central Bay Tributaries					
Del Presidio Crk. (CR_06B)	−122.543	37.903	0.707632 (7)	0.512508 (9)	−2.50
Corte Madera Crk. (CR_07B)	−122.557	37.962	0.707873 (7)	0.512471 (8)	−3.21
Central Bay Source Rocks					
Chert — Marin headlands (SFPCLF01)	−122.48120	37.83995	0.710967 (8)	0.512308 (7)	−6.40
Central Bay Beaches					
Crissy Field (SFPBCH19)	−122.46809	37.80685	0.705785 (8)	0.512497 (9)	−2.72
Angel Island (SFPBCH36)	−122.42044	37.85979	0.706498 (7)	0.512464 (8)	−3.35
Central Bay Offshore					
CBP05	−122.47079	37.81523	0.706099 (7)	0.512474 (8)	−3.16
CBP07	−122.46428	37.80840	0.706258 (7)	0.512486 (9)	−2.92
CBP11	−122.46077	37.82378	0.706110 (8)	0.512490 (6)	−2.86

(continued on next page)

Table 1 (*continued*)

Sample ID	Longitude (dec. degrees)	Latitude (dec. degrees)	$^{87}Sr/^{86}Sr$ (+/− $2\sigma\times10^6$)	$^{143}Nd/^{144}Nd$ (+/− $2\sigma\times10^6$)	εNd
Central Bay					
Central Bay Offshore					
CBP15	−122.45221	37.84142	0.706139 (8)	0.512574 (8)	−1.21
CBP19	−122.44835	37.80966	0.706182 (10)	0.512477 (9)	−3.10
CBP25	−122.43674	37.83179	0.706020 (7)	0.512485 (9)	−2.94
CBP26	−122.43744	37.82347	0.706168 (8)	0.512511 (7)	−2.44
CBP33	−122.42488	37.81576	0.706271 (7)	0.512558 (8)	−1.53
CBP37	−122.41187	37.86439	0.705837 (8)	0.512526 (7)	−2.14
CBP41	−122.39382	37.81988	0.706356 (7)	0.512488 (9)	−2.88
CBP42	−122.44054	37.87290	0.705932 (8)	0.512511 (7)	−2.43
CBP46	−122.44659	37.91482	0.705597 (8)	0.512543 (8)	−1.80
North Coast					
North Coast River					
Russian R. (CR_15A)	−122.99903	38.49935	0.707158 (10)	0.512585 (7)	−1.00
North Coast Source Rocks					
Sandstone — Rodeo Bch (SFPCLF03)	−122.54008	37.83198	0.708011 (7)	0.512562 (8)	−1.45
Granite — Pt. Reyes (SFPCLF07)	−123.01188	37.99768	0.709670 (7)	0.512295 (10)	−6.65
Fine Sandstone — Drakes Bay (SFPCLF08)	−122.96235	38.02596	0.708033 (6)	0.512344 (5)	−5.70
North Coast Beaches					
Rodeo Bch (SFPBCH17)	−122.53754	37.83070	0.706803 (7)	0.512569 (7)	−1.31
N. Pt. Reyes (SFPBCH27)	−122.98929	38.04856	0.707699 (7)	0.512505 (7)	−2.55
E. Drakes Bay (SFPBCH28)	−122.88324	38.02521	0.708013 (7)	0.512394 (7)	−4.72
Muir Beach (SFPBCH32)	−122.57566	37.85921	0.708816 (8)	0.512378 (6)	−5.03
North Coast Offshore					
OSP01	−123.00573	38.03457	0.707434 (7)	0.512451 (5)	−3.62
OSP05	−122.96114	37.98231	0.707892 (7)	0.512374 (8)	−5.11
OSP13	−122.80806	37.97768	0.709147 (8)	0.512327 (6)	−6.02
OSP22	−122.65687	37.89901	0.708739 (7)	0.512350 (7)	−5.58
OSP25	−122.58480	37.85441	0.708150 (7)	0.512418 (15)	−4.26
South Coast					
South Coast Source Rocks					
Granite — Gray Whale Cove (SFPCLF05A)	−122.51526	37.56733	0.705754 (8)	0.512628 (8)	−0.16
Sandstone — Ft Funston (SFPCLF09)	−122.50553	37.72099	0.705656 (0)	0.512454 (6)	−3.55
Sandstone — Pt. San Pedro (SFPCLF11) [b]	−122.52050	37.59413	0.709889 (9)	0.512214 (8)	−8.23
South Coast Beaches					
Montara SB (SFPBCH14)	−122.51480	37.54601	0.706279 (7)	0.512558 (7)	−1.52
N. Ocean Bch (SFPBCH21)	−122.51358	37.77498	0.705977 (9)	0.512536 (9)	−1.94
S. Ocean Bch (SFPBCH22)	−122.50773	37.73566	0.704812 (8)	0.512466 (7)	−3.32
Pacifica SB (SFPBCH25)	−122.50324	37.59820	0.707045 (8)	0.512416 (9)	−4.30
Fort Funston (SFPBCH40)	−122.50565	37.72099	0.705144 (9)	0.512465 (7)	−3.34
N. Mid Ocean Bch (SFPBCH42)	−122.51177	37.76002	0.705366 (8)	0.512555 (8)	−1.57
South Coast Offshore					
OSP28	−122.51382	37.73446	0.706084 (8)	0.512552 (7)	−1.63
OSP31	−122.50303	37.69658	0.706091 (7)	0.512538 (6)	−1.91
OSP35	−122.49811	37.63870	0.705800 (8)	0.512479 (7)	−3.05
OSP39	−122.51948	37.58324	0.707418 (7)	0.512410 (9)	−4.41

[a] Measured ratios normalized to SRM 987 $^{87}Sr/^{86}SR$=0.710248 and to La Jolla $^{143}Nd/^{144}Nd$=0.511858, both relative to the barrel averages.
[b] Samples are a composite of regional rock samples. Latitude/Longitude coordinates are a representative location.

varieties of rocks in the United States, consisting mostly of greywacke (~80%), shale and siltstone (10%), mafic volcanic rocks (6%), chert (3%), and conglomerate, limestone, and schist (<1%). Much of the Franciscan Complex has been intruded by ultramafic rocks, mostly serpentinite.

The San Francisco Bay coastal system comprises four sub-embayments (Suisun, San Pablo, Central, and South Bays), as well as the open-coast littoral cell that extends from Pt. Reyes to Pt. San Pedro, the ebb-tidal delta (i.e., San Francisco Bar), the inlet throat (i.e., Golden Gate), and the Sacramento–San Joaquin Delta mouth (Fig. 1). Fluvial sediment is derived from the watersheds of the Sacramento–San Joaquin Rivers as well as a host of smaller streams and drainages that either empty directly into the Bay or into the adjacent Pacific Ocean. For a more detailed description of the study area, see Barnard et al. (2012) and references therein.

3. Methods

3.1. Sample collection and preparation

A total of 253 surface sediment and rock samples were collected for this study. This sample suite represents all major fluvial inflows into the Bay, offshore surface sediments both within and external to the Bay, beach sediments, and dominant bedrock outcrops. A subset ($n = 87$) of these samples was selected for isotopic, REE, and trace element analyses and includes 16 beach, 46 grab, 10 rock, and 15 tributary samples. Bed sediment was collected from the Sacramento and San Joaquin Rivers and also from nine smaller tributaries that drain directly into the Bay (Napa and Guadalupe Rivers and Alameda, Calaveras, Corte Madera, Wildcat, Del Presidio, Sonoma, and San Francisquito creeks), as well as the Russian River, which drains into the Pacific Ocean north of Bodega Bay. Representative source rock samples were collected at sub-aerial outcrops along the open coast and represent the major geologic rock sources (i.e., granite, basalt, chert, sandstone, and serpentinite).

All sediment samples used for geochemical analyses were first cleaned with hydrogen peroxide to remove any organics, washed with ultra-pure, de-ionized water to remove salts, and then dried. The mud, sand, and gravel fractions were separated with sieving to yield a consistent sand fraction (0.15–0.5 mm). Shell fragments were subsequently removed with a 1 N HCl leach and the sample was rinsed thoroughly with ultra-pure de-ionized water generally following the procedures in Wei et al. (2012) and Meyer et al.

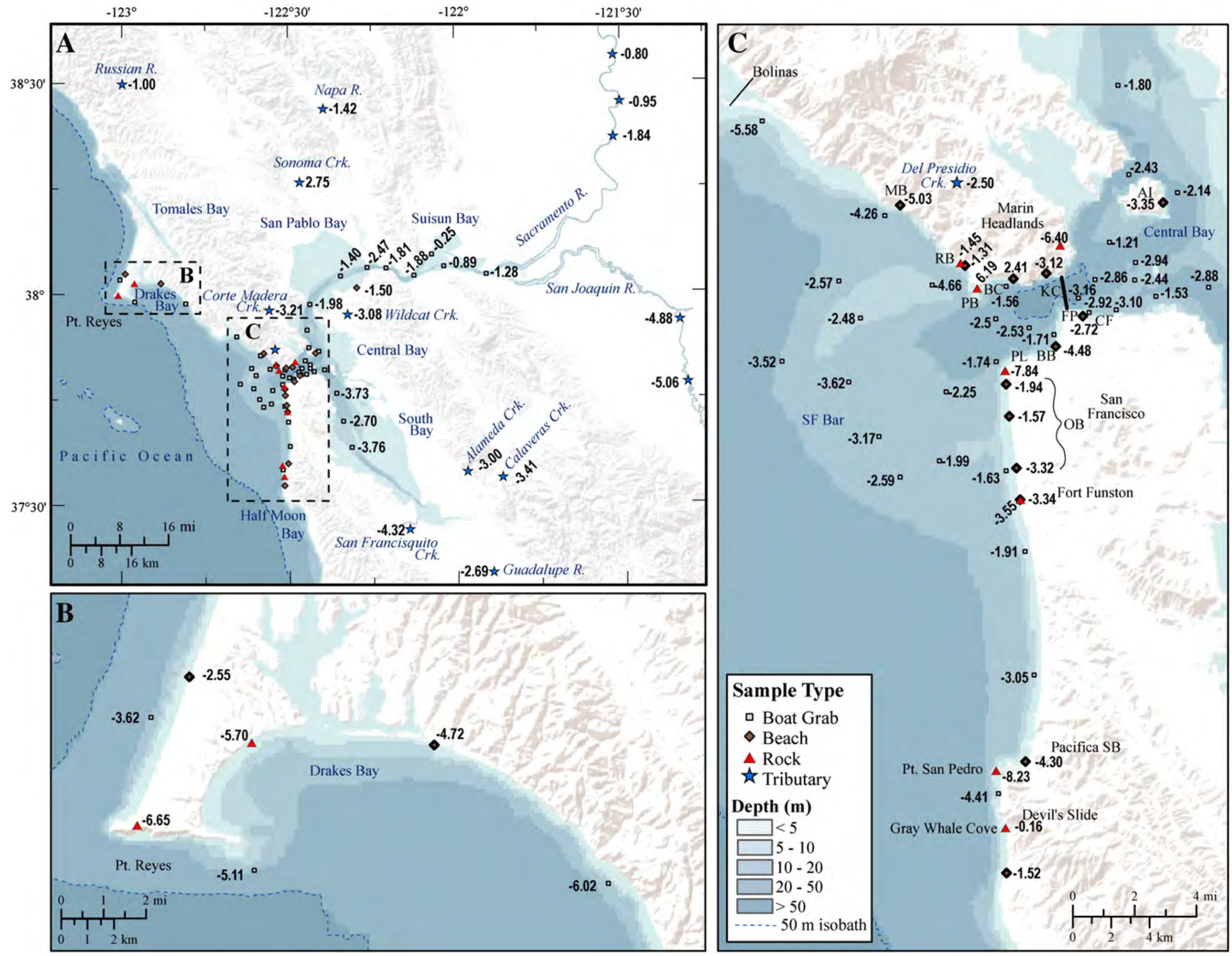

Fig. 2. Geographic distribution of εNd values (OB = Ocean Beach, PL = Pt. Lobos, FP = Fort Point, CF = Crissy Field, KC = Kirby Cove, BC = Bonita Cove, PB = Pt. Bonita, RB = Rodeo Beach, MB = Muir Beach, AI = Angel Is).

(2012). After being pulverized into a fine powder, bedrock samples were also leached and cleaned in the same manner. See Barnard et al. (2012) for additional details on sample collection and preparation.

3.2. Sr–Nd isotopes

Isotopic analyses were conducted at the Pacific Centre for Isotopic and Geochemical Research (PCIGR), University of British Columbia, following procedures outlined in Weis et al. (2006). Briefly, approximately 100–250 mg of sample powder was fully digested using heated 48% HF and 14 N HNO_3 in high-pressure PTFE bombs. Digested samples were subsequently brought to dryness and reconstituted with 6 N HCl prior to ion exchange, where Nd and Sr were quantitatively isolated. Isotopic measurements of Sr and Nd were conducted using a Thermo Finnigan Thermal Ionization Mass Spectrometer (TIMS). The Sr and Nd isotopic ratios were normalized to correct for mass fractionation using $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$. The maximum uncertainty for $^{87}Sr/^{86}Sr$ was ± 0.000010 and for $^{143}Nd/^{144}Nd$ ± 0.000015. $^{143}Nd/^{144}Nd$ ratios were converted to εNd using a value of 0.512636 for CHUR (chondritic uniform reservoir).

3.3. Trace elements and REE

Thirty three major, minor, trace and rare earth elements were analyzed by SGS Minerals Services. Each digested sediment sample was fused with lithium metaborate, dissolved using dilute HNO_3, and analyzed by high-resolution inductively-coupled plasma mass spectrometry (HR-ICP-MS). Precision with known calibration materials was within 2σ error of literature and recommended values. Procedural duplicates and replicate measurements show excellent agreement, with relative standard deviations (RSD) less than 5%. REE values were chondrite-normalized using values reported in Anders and Grevesse (1989). Ce and Eu anomalies were calculated using the formulas provided by Bau et al. (1996).

4. Results and discussion

A full compendium of all geochemical analyses, grouped geographically and subdivided based on sample type (fluvial, rock, beach, or offshore), is available for download from Pangaea (http://doi.pangaea.de/10.1594/PANGAEA.803904). Table 1 shows the normalized Sr–Nd

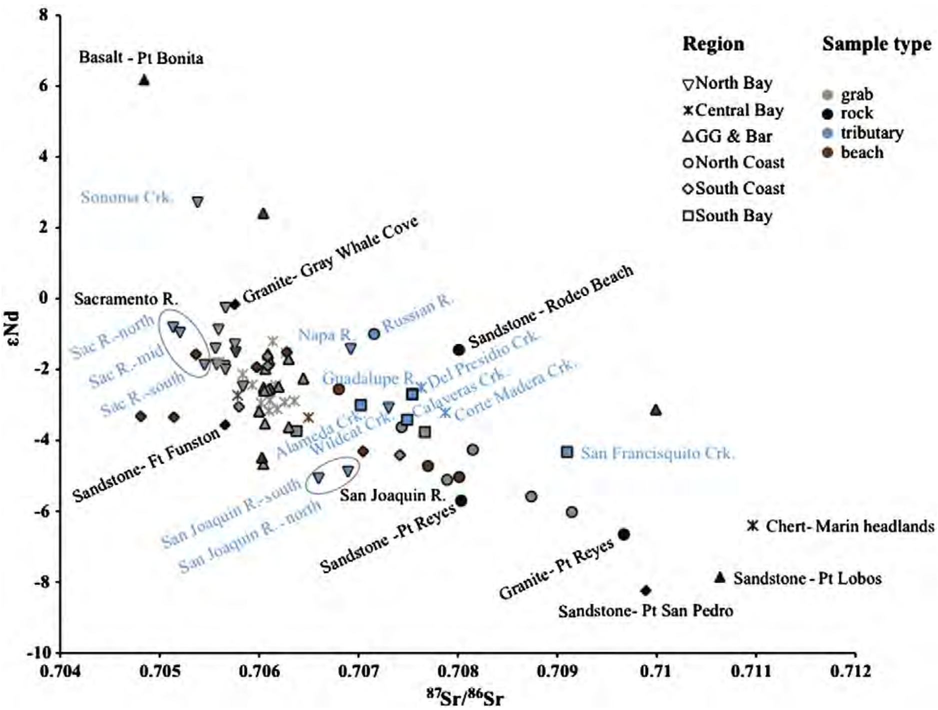

Fig. 3. εNd versus $^{87}Sr/^{86}Sr$ isotopic ratio. Symbols represent geographic region as well as sample type.

isotopic ratios and εNd data grouped geographically and subdivided based on sample type (fluvial, rock, beach, or offshore, $^{87}Sr/^{86}Sr$ ratios in the fluvial inflows and in the source rock samples ranged from 0.705138 to 0.709098 and 0.704841 to 0.710967, respectively. Normalized $^{143}Nd/^{144}Nd$ ratios ranged from 0.512376 to 0.512777 in the 15 tributary samples to 0.512214 to 0.512953 in the representative source rock samples. εNd values for the 15 tributary samples ranged from −5.06 to 2.75, while εNd for the 10 source rocks showed an even greater range from −8.23 to 6.19 (Fig. 2). Isotopic characterization of representative fluvial and rock outcrop samples provide robust end members against which Bay sediment can be compared. The large variability shown in these potential source terms and the geochemical stability suggest that εNd is likely the most useful tracer to examine sand-sized sediment movement through the San Francisco Bay.

A plot of εNd versus $^{87}Sr/^{86}Sr$ (Fig. 3) is useful for visualizing how sediment samples relate to one another and to each other and potential sources. The data are plotted by geographic region and sample type. For example, it is clear how the fluvial input from the San Joaquin River differs from the Sacramento River. Other tributaries and source rocks are plotted in blue and in black respectively. Sediment samples within geographic regions generally cluster within narrow groups except for the North Coast samples that appear to be on a mixing line discussed below.

The chondrite-normalized REE concentrations (http://doi.pangaea.de/10.1594/PANGAEA.804474) in inflowing tributaries show overall uniform light-REE (LREE) enriched patterns with median $La/Yb_{(N)}$ and $Y/Ho_{(N)}$ values of 5.22 (3.96 to 9.73) and 0.52 (0.47 to 0.55) respectively. In contrast, the source rock samples exhibit median $La/Yb_{(N)}$ and $Y/Ho_{(N)}$ values of 5.32 (3.61 to 13.99) and 0.56 (0.47 to 1.12) respectively. These relatively steep REE patterns, expressed by high $(La/Yb)_N$ values, are a result of fractionation induced by garnet-rich melting residues and have been used as proxies for estimating the origin of lithogenic aluminosilicates.

The geographic distribution of the total REE abundances is plotted by sample type in Fig. 4. The total REE abundance appears elevated in most of the source rocks relative to the beach and offshore sediments except for the very high total REE abundance along Ocean Beach that is apparently related to the high magnetite content at this locale. The total REE abundance in the fluvial input from the San Joaquin River is higher than in the Sacramento River and evident in sediment in the North Bay embayments.

The median chondrite-normalized REE patterns are plotted by geographic sub-region in Fig. 5 with patterns for the Sacramento and San Joaquin River samples displayed on each sub-plot for reference. The profiles of the beach and offshore sediment are generally bounded by and in some cases coincident with the fluvial inputs and source rocks. For example within the North Bay, except for the heavy REE, beach sediment follows the trend of the Sacramento River whereas offshore sediment is more consistent with local tributary samples (Fig. 5). In the South Bay the pattern for offshore sediment is nearly coincident with the pattern for the local tributaries (Fig. 5). Similarly for the North Coast, the pattern for offshore sediment is coincident with the pattern for beach sediment. These and other REE relationships are discussed below in the context of isotope and trace element results for each sub region.

Select trace element concentrations are also available for download at Pangea (http://doi.pangaea.de/10.1594/PANGAEA.804474). Hf and Zr are products of continental weathering and erosion and are conveyed to the oceans principally by rivers. Zirconium and Hf are chemically very similar, and as a result, the atomic Zr/Hf ratio exhibits a narrow range of 70 to78 (Godfrey et al., 2008). Expectedly, the representative source rock samples exhibited the highest trace element concentrations, while the offshore sediment grab samples generally had the lowest trace element concentrations. Both the Zr/Hf and Ni/Zr ratios were useful discriminants ranging widely in values from 28 to 96 and from near 0 to 1.6 (excluding one value of 207 for serpentinite at Fort Pt.) respectively. Median Zr/Hf and Ni/Zr ratios of the sources were most similar to sediment samples collected from Central Bay and showed the greatest difference relative to the offshore, Golden Gate, and bar sediment samples (Figs. 6 and 7).

4.1. Tracing sediment sources and pathways

Sediment of the San Francisco Bay coastal system is derived from highly varied sources and subject to complex transport and mixing processes. Sources include rivers that erode the distant Sierra Nevada granitic and metamorphic rocks and feed into the rivers of the Great Valley, the erosion of the Pacific Coast Ranges that are composed of the heterogeneous Franciscan Complex rocks, displaced Sierran granites, and Mesozoic and Cenozoic sedimentary and volcanic rocks, and sediment transported by long-shore drift along the coastal ocean. Each of these sources may have characteristic isotopic and compositional signatures that can be used in combination to decipher likely sand sources.

Provenance was assessed regionally by examining the geographic distribution of Sr–Nd isotopes, REEs, and select trace elements. For the ensuing discussion, the San Francisco Bay coastal system is separated into the following five sub-systems: 1) North San Francisco Bay, including, the Bay Delta, the Sacramento and San Joaquin Rivers, and the Suisun, San Pablo, and north Central Bays along with local tributaries; 2) South Bay and tributaries; 3) the Golden Gate (GG) extending from the outer bar to Angel Island in Central Bay; 4) the North Coast from the Pt. Bonita to the Russian River, and 5) the South Coast from Pt. Lobos to Half Moon Bay.

4.1.1. North San Francisco Bay

Fig. 2 portrays εNd values geographically from all samples collected in the San Francisco Bay coastal system. The main source for sediment to Suisun, San Pablo, and north Central Bays is as expected the Sierra Nevada via the Sacramento River. Indeed, εNd values for the Sacramento River samples (−0.8, −0.95, −1.84) are clearly distinct from San Joaquin River samples (−4.88, −5.06) and are very similar to sediment samples collected from the North San Francisco Bay channel and beach (−0.89 to −1.98). One sample in San Pablo Bay had an anomalous εNd of −2.47, which indicates some other input, possibly from a local tributary such as Wildcat Creek (εNd = −3.08), or dilution by San Joaquin River or sediments transported from Central Bay. A plot of εNd versus $^{87}Sr/^{186}Sr$ (Fig. 3) and geographic plots of the total REE (Fig. 4) confirm that the majority of sediment in North Bay derives from the Sacramento River with additional inputs from the San Joaquin and local rivers.

4.1.2. South Bay

South Bay is unique as a sub-system with fluvial inflows limited to several small tributary inputs at the southern reaches of the bay (San Francisquito, Alameda and Calaveras Creeks, Guadalupe River). Surface sediments are comprised primarily of silts and clays with occasional shell hash. We were unable to obtain a sufficient amount of sand from the majority of South Bay samples and our analyses were limited to only three samples in the northern half of South Bay. While the extreme south end of the bay has experienced a net accretion of sediment since

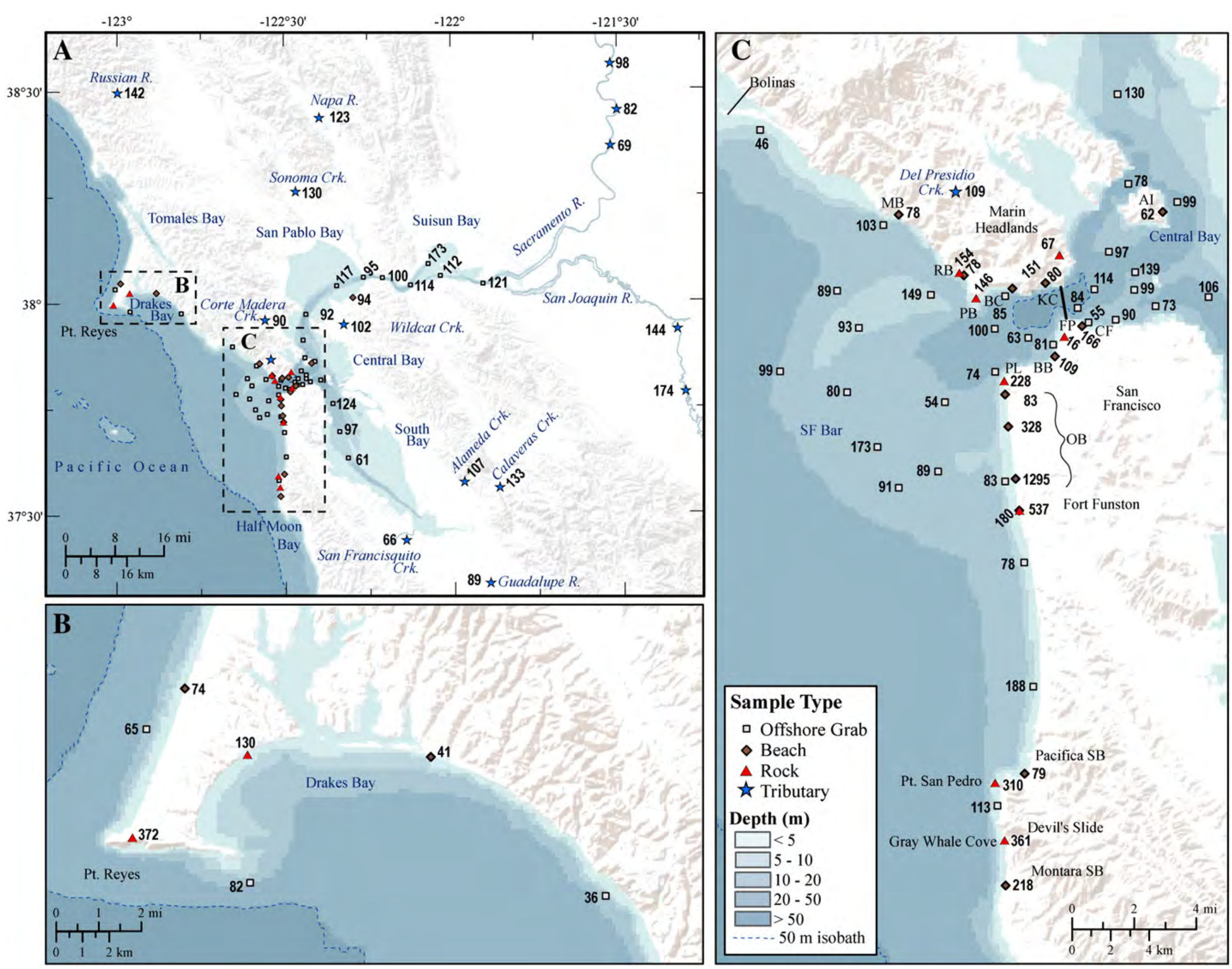

Fig. 4. Geographic distribution of total rare earth element (ΣREE) abundances. Yttrium (Y) is excluded from this summation because Y was not analyzed for every sample (OB = Ocean Beach, PL = Pt. Lobos, FP = Fort Point, CF = Crissy Field, KC = Kirby Cove, BC = Bonita Cove, PB = Pt. Bonita, RB = Rodeo Beach, MB = Muir Beach, AI = Angel Is).

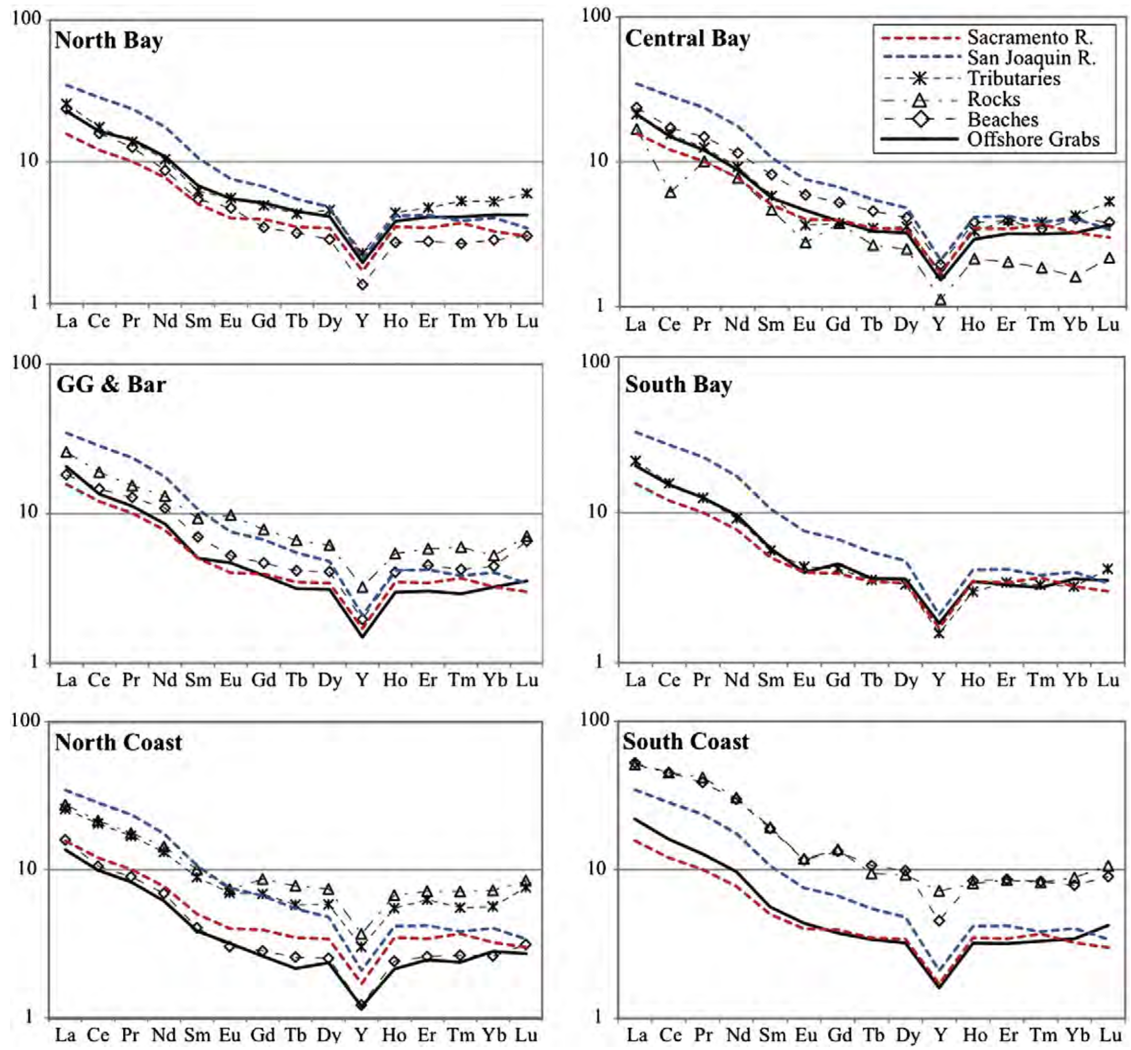

Fig. 5. Median chrondite-normalized REE concentrations by geographic sub-region. Sacramento and San Joaquin River samples are displayed on each plot for reference.

the 1850s, sedimentation trends in the northern portion of the bay have been variable through time (Foxgrover et al., 2004) and exchange with Central Bay poorly understood. The εNd values (Figs. 2 and 3) and the REE distribution (Fig. 4) suggest that the primary source of sediment in South Bay (−2.7 to −3.76) is a mixture of sediment derived locally from the Guadalupe River (−2.69) and the Alameda (−3) and Calaveras Creeks (−3.41). The distribution of the trace element ratios Ni/Zr and Zr/Hf (Figs. 6 and 7) also indicate sediment derived from these local fluvial sources. Other studies have found that dissolved concentrations of many trace elements (copper, nickel, cadmium, zinc, and cobalt) in the South Bay are anomalously high relative to concentrations at comparable salinities in the Central Bay and northern embayments, primarily due to enhanced anthropogenic inputs (waste-water discharges and urban runoff) and diagenetic remobilization from benthic sediment (Flegal et al., 1991). Sediment sources may also include a marine contribution that would be conveyed into the northerly portion of South Bay from the energetic tidal exchange at the mouth of the Bay.

4.1.3. Golden Gate

The representative source rocks of this sub-system exhibited the largest range in εNd (Fig. 3; Table 1); −7.84 (Pt. Lobos Sandstone) to 6.19 (Pt. Bonita Basalt). A large range in εNd is also seen in beach sands (−4.48 to 2.41) and the Golden Gate (GG) and bar offshore sediment samples (−4.66 to −1.56). The pattern in εNd among major sources for sand around the Golden Gate from the outer bar to Angel Island in Central Bay all indicate a zone of energetic sediment mixing that involves multiple distinct sources. This mixing zone represents a confluence of sediment transport long-shore from the North Coast, westward from the Sacramento and Napa Rivers, and near-shore northward from Ocean Beach through the Golden Gate into the upper South Bay. These sands cluster together within a narrow band around a Sr isotopic ratio of 0.706 (Table 1) with a range in εNd from -1 to −5 (Figs. 2 and 3; Table 1). The εNd value from a sediment sample from Baker Beach (−4.48) is close to that of sand from along the north coast (−4.66). Both the εNd and the Sr isotopic ratios suggest that local sediment sources are also important in this region, such as contribution from basaltic outcrop at Bonita Point to sand in Bonita Cove and from chert from the Marin Headland to sand in Kirby Cove. The REE distribution for Golden Gate and bar sediment samples falls close to the Sacramento River values (Fig. 5), indicating an important source.

4.1.4. North Coast

Sediment samples for this sub-system are from around Pt. Reyes and within Drakes Bay as well as a few samples collected south of Bolinas along the coast towards the Golden Gate. The εNd values are generally highly depleted in this subsystem (Figs. 2 and 3), reflecting local

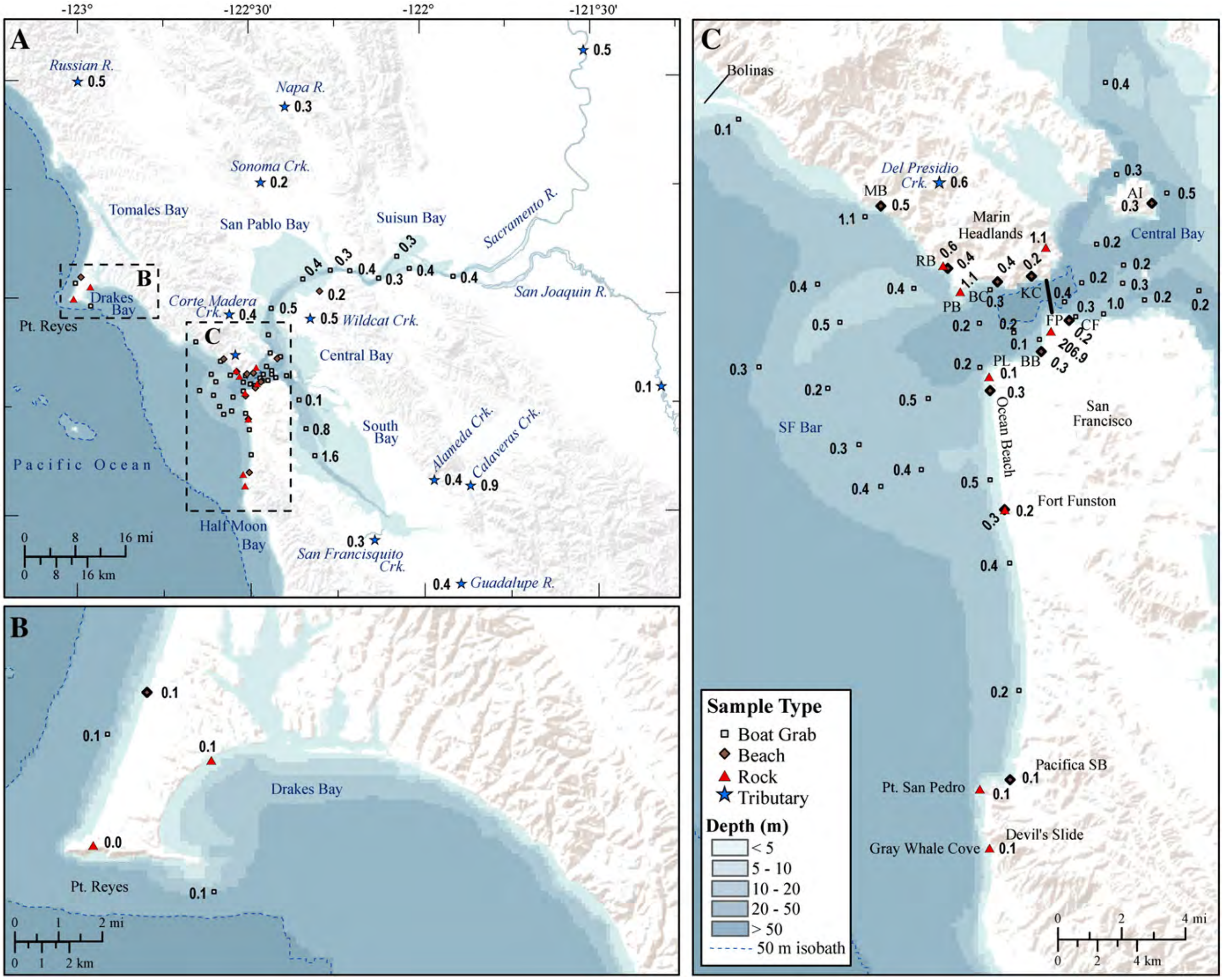

Fig. 6. Geographic distribution of Ni/Zr (OB = Ocean Beach, PL = Pt. Lobos, FP = Fort Point, CF = Crissy Field, KC = Kirby Cove, BC = Bonita Cove, PB = Pt. Bonita, RB = Rodeo Beach, MB = Muir Beach, AI = Angel Is).

contributions such as from the Pt. Reyes granite (−6.65) and sandstone (−5.7). Based on εNd and Zr/Hf values, the outer coast sands are primarily derived from alluvium and sandstone outcrops and may possibly retain a signal that reflects sediment from the distal Russian River (−1.0, 34, respectively). It has been documented that fine-grain material is transported from the Russian River around Pt. Reyes and southward so it is reasonable to hypothesize that sand-size material could also be likewise transported. With just a couple of data points along the outer North Coast, it is not possible to make a definite conclusion but because the isotopic data fall between the value for the Russian River and values for the reference samples at Pt. Reyes mixing is a possibility. And as plotted in Fig. 3 there does appear to be a mixing trend in all the north coast isotopic data between sediment from the Russian River and both sandstone and granite at Pt. Reyes. Along the inner coast of Pt. Reyes it is likely that the sands are derived mostly from local sources such as the sandstone cliffs composed of marine terrace deposits within Drakes Bay and the Salinian granitic headland as well as some sediment that is transported around the headland from the outer coast. This trend is confirmed in the REE distribution where concentrations offshore match beach samples (Fig. 5). The geographic pattern of εNd values in Drakes Bay suggests that eddy currents might redistribute sands within this embayment while long-shore currents convey these sands southward where they are eventually mixed with other locally derived, geochemically similar marine deposits such as the Santa Margarita Sandstone.

4.1.5. South Coast

The beach and offshore sands along the outer coast south of the Golden Gate are a mix of sediment transported alongshore from north of the Golden Gate, sediment that has exited the Bay mouth and is conveyed southward, and local source rocks. Local sources include the Merced Formation, steep sandstone cliffs at Fort Funston, and the granitic cliffs near Devil's Slide (Fig. 2). Based on εNd values (Figs. 2 and 3), the beach sands at Pacifica State Beach are similar to the offshore sands south of San Pedro, but do not convey the strongly depleted signal of the San Pedro sandstone (−8.23). Neither the Pt. Lobos sandstone nor the Pt. San Pedro sandstone appear to be significant sediment sources. The beach sand at the south end of Ocean Beach appears to be related to the Pleistocene Colma Formation that overlies the Pliocene and Pleistocene Merced Formation from Fort Funston south (Schlocker, 1974) and is characterized by a high magnetite content. This geochemical signal dissipates to the north to mid-Ocean Beach and to the south to Fort Funston. The REE distribution (Fig. 5) implies that the grab samples are bounded by the Sacramento and San Joaquin River values.

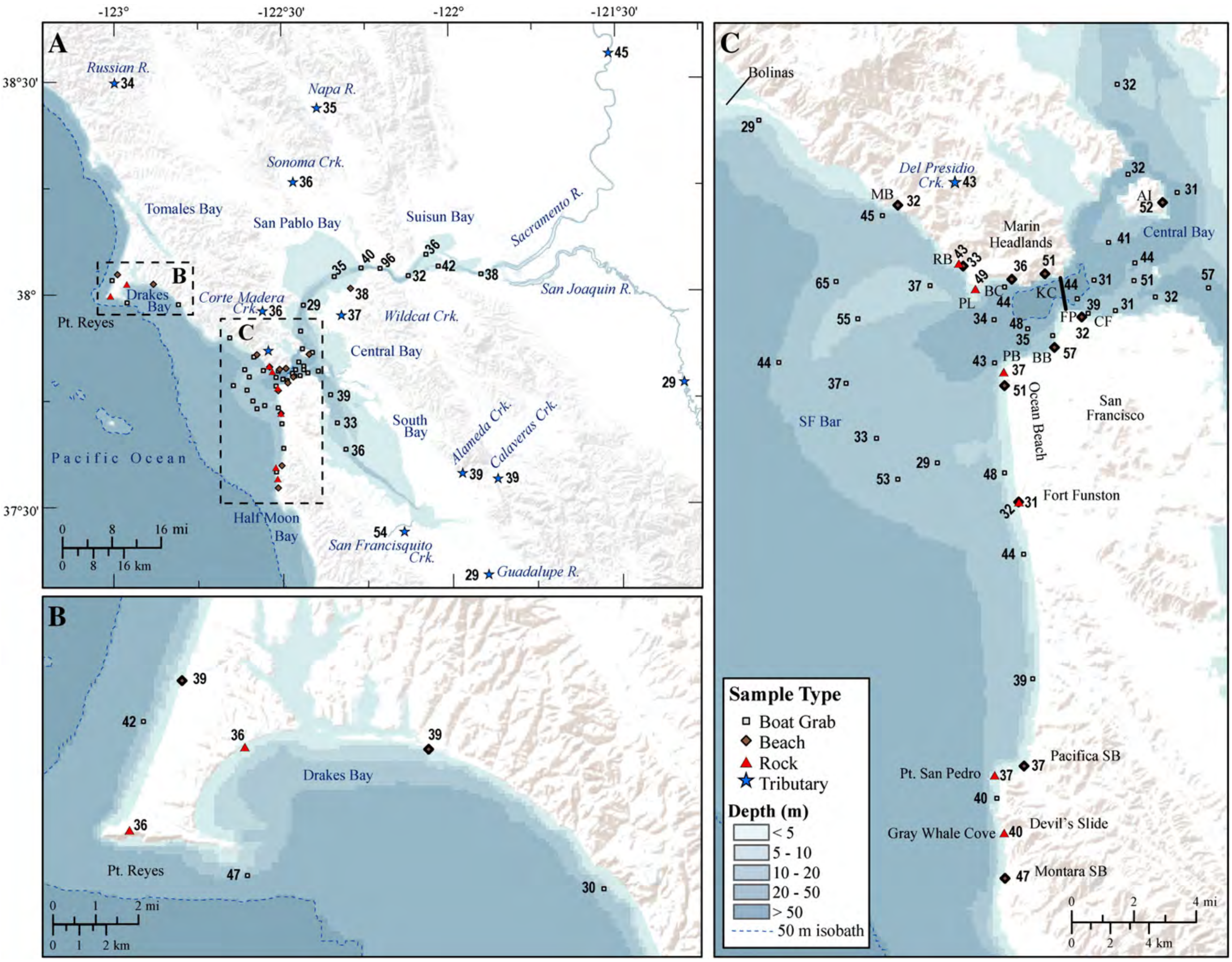

Fig. 7. Geographic distribution of Zr/Hf (OB = Ocean Beach, PL = Pt. Lobos, FP = Fort Point, CF = Crissy Field, KC = Kirby Cove, BC = Bonita Cove, PB = Pt. Bonita, RB = Rodeo Beach, MB = Muir Beach, AI = Angel Is).

5. Conclusions

Sr–Nd isotope ratios and to a lesser extent the REE and ratios of trace elements were used to infer beach-sized sand transport pathways through the San Francisco Bay coastal system. Sr–Nd isotopes show that the predominant source of beach-sized sand to Suisun Bay, San Pablo Bay, and north Central Bay is the Sierra Nevada via the Sacramento River, with additional local contributions to San Pablo Bay from the Napa River. The REE data also imply that some sediment is introduced into Suisun Bay and San Pablo Bay from the San Joaquin River. Based on the isotopic signatures, once sand-sized sediment exits San Francisco Bay proper, it is then conveyed southward along the outer coast by long-shore currents. Isotopic ratios also reveal localized regions of source rocks and sand accumulation, such as the basalt and chert deposits close to the Golden Gate. Sands in the northern portion of South Bay are derived from local tributaries, such as Alameda Creek, with no sediment evident from the Sacramento or San Joaquin Rivers. On the outer coast of Pt. Reyes north of the Golden Gate Bridge, sand-sized material is sourced both locally (sandstone and granitic outcrops) and possibly from the distal Russian River with additional contributions from local streams. The predominant provenance of sand along the coast north of the Golden Gate is from beach-backing sandstone cliffs along the coast north to Pt. Reyes. This sand mixes with sediment exiting the Golden Gate and some of this mixed sand is carried back into Central Bay and partly into South Bay through tidal currents; some of this mixed-source- sand is also transported southward along the coast south of the Golden Gate. Consequently, the beach and offshore sands along the coast south of the Golden Gate are composed of an amalgamation of sand transported alongshore from north of the Golden Gate mixed with sediment derived from within the Bay, primarily from the Sacramento River, and material derived from local outcrops and creeks. Distinct transport pathways were not discernible from the REE results alone, but they aided in interpretation of the isotopic data.

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Exhibit I

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Heavy mineral analysis for assessing the provenance of sandy sediment in the San Francisco Bay Coastal System

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ABSTRACT

Heavy or high-specific gravity minerals make up a small but diagnostic component of sediment that is well suited for determining the provenance and distribution of sediment transported through estuarine and coastal systems worldwide. By this means, we see that surficial sand-sized sediment in the San Francisco Bay Coastal System comes primarily from the Sierra Nevada and associated terranes by way of the Sacramento and San Joaquin Rivers and is transported with little dilution through the San Francisco Bay and out the Golden Gate. Heavy minerals document a slight change from the strictly Sierran-Sacramento mineralogy at the confluence of the two rivers to a composition that includes minor amounts of chert and other Franciscan Complex components west of Carquinez Strait. Between Carquinez Strait and the San Francisco Bar, Sierran sediment is intermingled with Franciscan-modified Sierran sediment. The latter continues out the Gate and turns southward towards beaches of the San Francisco Peninsula. The Sierran sediment also fans out from the San Francisco Bar to merge with a Sierran province on the shelf in the Gulf of the Farallones. Beach-sand sized sediment from the Russian River is transported southward to Point Reyes where it spreads out to define a Franciscan sediment province on the shelf, but does not continue southward to contribute to the sediment in the Golden Gate area.

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1. Introduction

The San Francisco Bay Coastal System encompasses the geologic and hydraulic character, source, transport, and deposition of sediment of the Sacramento–San Joaquin delta, San Pablo Bay, Central Bay, South Bay, the San Francisco Bar, and the open coast north and south of the Golden Gate. Sediment flows into and through the system from major rivers — the Sacramento and San Joaquin and small streams (Barnard et al., 2013b–this issue). Heavy mineral analyses are here described as part of a multi-faceted study to more precisely trace sediment transport through this system to address issues such as sea-level rise, coastal vulnerability, and sediment economics (Barnard et al., 2013b–this issue). This sample set was also analyzed for grain size (Barnard et al., 2013b–this issue), mineralogy by X-ray diffraction (Hein et al., 2013–this issue), rare earths and trace elements (Rosenbauer et al., 2013–this issue), and biologic components (McGann et al., 2013–this issue).

Heavy minerals (specific gravity 2.85 or greater) have been used to determine sediment provenance or source in many geologic environments (Mange and Wright, 2007), including the Nile delta (Frihy and Lawrence, 2004), turbidites of the mid-ocean Juan de Fuca Ridge (Zuffa et al., 2000), Escanaba Trough in Gorda Ridge (Normark et al., 1994; Wong, 1989), and the eastern Irish coastal zone (Malone, 2007). The heavy minerals are a small part of the sediment volume, but – unlike the commonplace quartz, feldspar, and micas in the complementary light fraction – consist of a variety of minerals and other components that can point to sources of sediment ranging from general to precise locations. In the San Francisco Bay area, much work on the heavy minerals has been presented that provide a framework for provenance of sands (see Prior work—sediment transport, Barnard et al., 2013a–this issue). The samples from this study complement earlier work with an expanded number of samples and provide data for the specific set of samples simultaneously analyzed by other methods.

2. Geologic setting

The major watersheds feeding sediment into the San Francisco Bay Coastal System are the Sacramento and San Joaquin River drainages from the California Central Valley, which draw from the Sierra Nevada granitic rocks and foothill metamorphic rocks in the east, and Great Valley Complex (consisting of Great Valley Group sedimentary rocks and Coast Range Ophiolite) in the western part of the watershed (Elder, 2013–this issue; Fig. 1). The combined watershed of these two rivers is about 154,000 sq km (Table 1). Sediment delivery from these watersheds has progressively decreased due to agricultural practices and urban water needs. McKee et al. (2013–this issue), focusing on the fine fraction (<0.062 mm) of the suspended sediment load, have determined that much of the modern sediment introduced into San Francisco Bay may come from smaller (<2000 sq km) watersheds that rim the Bay. Various tectonic terranes of the Franciscan Complex underlie parts of most of the following watersheds: Corte Madera and Del Presidio Creeks in Marin County, Wildcat Creek in the East Bay, and Alameda, Calaveras,

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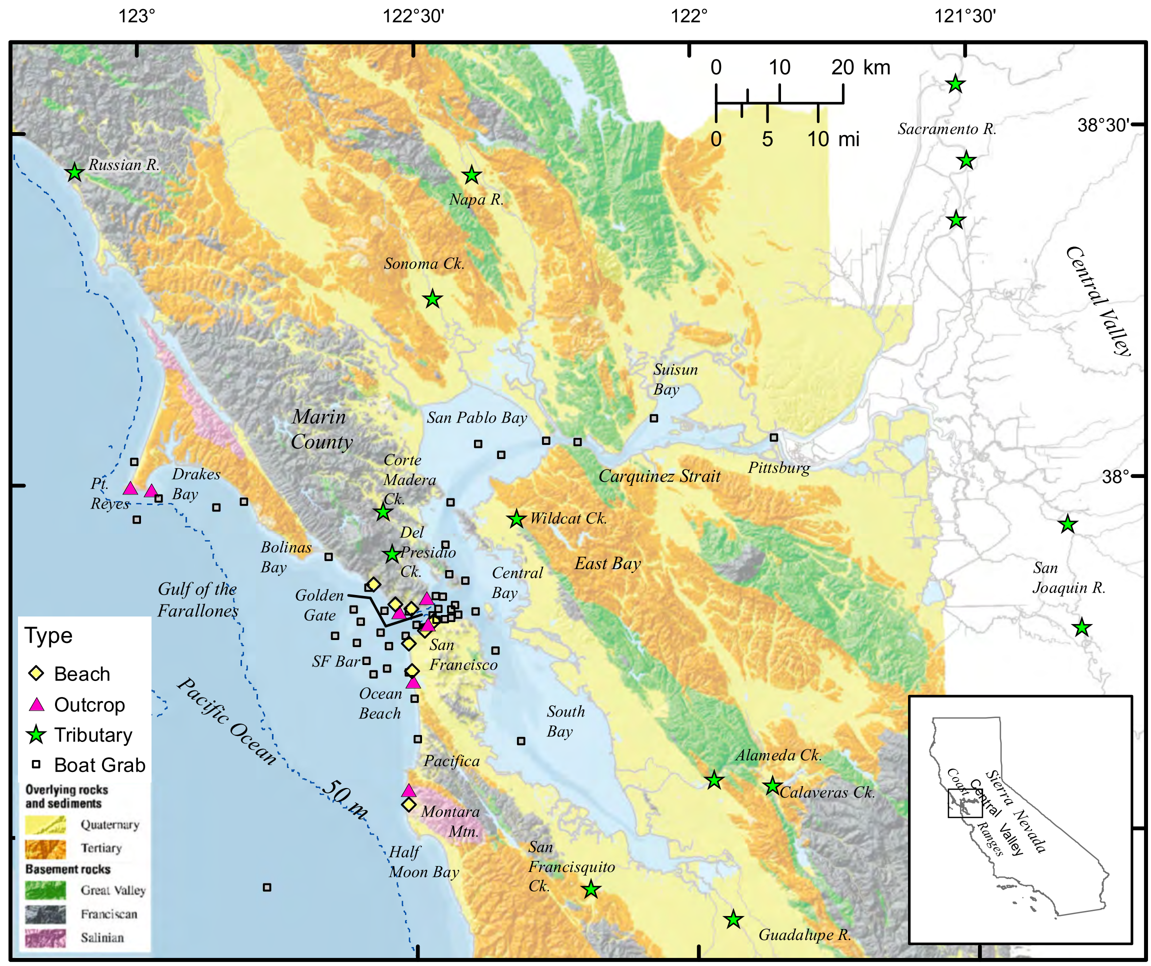


Fig. 1. Location of samples analyzed for heavy minerals. Base map shows the generalized geology of the San Francisco Bay Coastal System (Graymer et al., 2006).

and San Francisquito Creeks and Guadalupe River in South Bay (Table 1). Tertiary Sonoma Volcanics are the dominant rock type draining the Sonoma Creek watershed and accompany the Franciscan and Great Valley Complex rocks in the Napa River watershed (Wagner et al., 2011; Elder, 2013–this issue). On the open coast to the north, the Russian River watershed (3500 sq km) drains Franciscan Complex lithology that appears in coastal sediment migrating southward in response to the California Current (Yancey and Lee, 1972; Noble, 2001). From the Russian River mouth southward, nearshore coastal sediment is also drawn from erosion of outcrops of the Franciscan Complex and overlying Tertiary sedimentary rocks, granitic rocks in the Point Reyes area, more Franciscan in Marin County and the northern San Francisco peninsula, younger sedimentary rocks (Merced Formation) and granitic rocks from Montara Mountain (Elder, 2013–this issue). Seaward of a narrow coastal zone north and south of the Golden Gate, surficial sand in the Gulf of the Farallones is identified with the Sierran sediment from the Sacramento–San Joaquin watersheds. West and south of Point Reyes, the seafloor sediment is characterized by heavy minerals from Franciscan Complex sources (Wong, 2001).

3. Previous work

Hall (1965), in his pursuit of a source for the Plio-Pleistocene Merced Formation on the western San Francisco Peninsula, examined heavy minerals from major drainages in the Central Valley, local streams flowing into the San Francisco estuary, and from the San Francisco Bar. Gram (1966) examined samples in South Bay. Outside the Golden Gate heavy minerals have been examined from coastal and nearshore zones from the Russian River mouth to Half Moon Bay (Cherry, 1966; Moore, 1965; Sayles, 1965). Most of these studies extracted heavy minerals from sediment in the 2- to 4-phi range, while others either looked at a narrower size range or looked at all sand in 0.5-phi intervals. Their heavy minerals were separated in liquids with specific gravity ranging from 2.88 to 2.95 and each sample was counted to identify at least 100 nonopaque grains.

The mineralogic data from these studies were integrated by Johnson (1971) and Yancey and Lee (1972). The best recognized sources of sediment are material from the Sierra Nevada channeled through the Central Valley into San Francisco Bay and from the Franciscan Complex exposed within San Francisco Bay and from the Russian River. The trend persists in sediment on the shelf, where two primary depositional provinces are characterized by either Sierran or Franciscan minerals (Wong, 2001; Barnard et al., 2013b–this issue).

4. Methods

The sample set for the San Francisco Bay Coastal System provenance study consists of surficial sediment samples collected in 2010–2012 from beaches and seafloor from the Central Valley to the San Francisco Bar and the open coast north and south of the Golden Gate (Barnard et al., 2013b–this issue). Samples to determine source materials were collected from streams and cliff outcrops facing the Golden Gate and Pacific Ocean (Fig. 1). The sediment samples were cleaned of organic material using hydrogen peroxide, washed with deionized water, and dried. Samples were sieved to separate mud (<0.063 mm), sand (0.063 to 2.0 mm), and gravel (>2.0 mm) size fractions. Grain size analyses were conducted

Table 1
Characteristics of streams providing sediment San Francisco Bay and north coast.

Sample ID	Description	Watershed	Watershed area (sq km)[a]	Annual fine suspended sediment load (metric t)[a]	Watershed geology[b]	Mineralogy (this study)	Class
SAC01, SACFP, SACHD	Sacramento River	Sacramento–San Joaquin	154,000	892,000	Sierra Nevada plutonic and metamorphic terranes, Grt Vly	Hornblende, hypersthene, augite, epidote, chlorite	1.2
SJC02, SJRST	San Joaquin River					Hornblende, zircon	1.3
CR_01	Wildcat Creek	East Bay	26	6703	Fran Cx, Grt Vly, CRO, QT, volc	Hornblende, glaucophane, epidote, zircon, garnet	2
CR_06B	Del Presidio Creek[c]	Marin County	21	NA	Fran Cx	Hornblende, basaltic hornblende, glaucophane, hypersthene, enstatite, epidote, sphene, garnet	2
CR_07B	Corte Madera Creek	Marin County	48	10,461	Fran Cx	Hornblende, enstatite, epidote, sphene, garnet	2
CR_10	Alameda Creek	Alameda Creek	1664	112,346	Fran Cx, Grt Vly, CRO, QT, volc	Basaltic hornblende, glaucophane, zircon	2
CR_11A1	Calaveras Creek	Alameda Creek		NA	Fran Cx, Grt Vly, CRO, QT, volc	Hornblende, glaucophane, enstatite, epidote, sphene, zircon, chert	4
CR_03	Napa River	Napa River	738	310,928	Sonoma Volc, Grt Vly, Fran Cx	Glaucophane, hypersthene, enstatite, augite, chert	5
CR_04	Sonoma Creek	Sonoma Creek	241	204,516	Sonoma Volc, Fran Cx	Epidote, enstatite, clinopyroxene, chert	5
CR_08	San Francisquito Creek	Peninsula	118	40,081	Fran Cx, CRO, QT	Enstatite, clinopyroxene, epidote, zircon, chert	5
CR_09	Guadalupe River (downstream end of Coyote Creek)	Coyote Creek and Guadalupe River	1279	16,205	Fran Cx, CRO, Grt Vly, QT	Glaucophane, hypersthene, augite, sphene, garnet	6
RR_VV2	Russian River	Russian River	3500	NA	Fran Cx	Glaucophane, augite, epidote	6

[a] Except for Del Presidio Creek and Russian River, watershed area and suspended sediment load data from McKee (2013–this issue). Other watershed data from USGS Water Data for California (http://waterdata.usgs.gov/ca/nwis).
[b] Fran Cx — Franciscan Complex, Grt Vly — Great Valley sedimentary rocks, CRO — Coast Range Ophiolite, QT Tertiary sediment, volc — volcanic rock.
[c] Full name of Del Presidio Creek is Arroyo Corte Madera del Presidio.

for the mud and sand fractions (Barnard et al., 2013b–this issue). From the 0.063–2.00 mm sand fraction, as much as 50 g of each of two size fractions (0.063 mm to 0.25 mm and 0.25 mm to 0.5 mm) were weighed out for heavy mineral analysis.

Outcrop samples from seven cliff locations (Fig. 1) yielded 17 rock samples that required separate processing. Polished thin sections of these samples were prepared for petrographic examination. The leftover rock chips from the thin section processing were ground up, sieved, and processed with the unconsolidated sediment.

Heavy minerals, characterized by higher specific gravity, are usually hydraulically concentrated in a smaller size fraction than the median or modal grain sizes of the bulk sediment sample (Hubert, 1971). The 0.063–0.25 mm (2 to 4 phi) size range was selected as optimal for optical identification. With the mean D10 to D90 range of the open coast beach samples ranging between 0.15 mm and 0.5 mm (1 to 2.75 phi; Barnard et al., 2013b–this issue), 2 to 4 phi (about one phi size smaller) would be representative of the bulk sample for most of those samples. Where there was not enough sand in the 0.063–0.25 mm fraction, samples from the 0.25–0.50 mm size fraction were substituted. Though we tried to analyze the same samples as for the other techniques, if there was insufficient volume in either size fraction, a sample from a nearby location was substituted.

The samples were separated in tetrabromoethane diluted to a specific gravity of 2.90. Both the light (float) and heavy (sink) mineral fractions were collected and weighed and all material retained. The heavy mineral separates were microsplit to provide about 1000 grains. Magnetic grains were removed before the sample was mounted in Araldite epoxy cement (refractive index 1.56) on a standard 47 $\times$ 26-mm glass slide with a cover slip.

Techniques for identifying chemical properties of specific heavy minerals and their abundance have included single-mineral studies by analytical methods such as electron microprobe and, more recently, sensitive high-resolution ion microprobe and laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS) (Mange and Morton, 2007). The method for examining multi-mineral populations (for example, Garzanti and Ando, 2007, or Malone, 2007) still relies on microscopic point-counting as described here. Mineral grains were identified based on optical properties with transmitted light on a petrographic microscope and occasionally supplemented by oblique illumination to view grain surface properties. Each sample slide was placed in a fixed orientation on a calibrated mechanical stage (label end in notch). Grains were examined along lines 1 to 2 mm apart. Commonly occurring minerals and types of rock fragments were tabulated to produce total and percentage counts. Counting progressed until, where available, at least 200 nonopaque (transparent) grains were identified to minimize probable error in mineral abundances (Galehouse, 1971).

The counts for all the grain mounts were tabulated and percentages of total grains counted for nonopaque, lithic (rock fragments), and opaque grains were calculated. To normalize the data for cluster analysis, the percent of total nonopaque (transparent) grains of each mineral species is calculated (Apx. 1). A Q-mode cluster analysis was applied to the nonopaque abundances, which grouped the samples according to their degree of mineralogic 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 (Clarke and Gorley, 2006).

5. Results

5.1. Geology of outcrop samples

Except for a friable sample (SFBCH09) from Ocean Beach that was processed with the unconsolidated sediment, the abundance of heavy minerals from outcrop samples that were crushed, sieved and separated is only qualitatively comparable to similarly sized grains in the unconsolidated samples. As the outcrops were sampled to determine possible source materials for the sediment in the San Francisco Bay Coastal System, we classify them by the geologic units from which they were sampled (Table 2). Samples from the Marin Headlands terrane of the Franciscan Complex (Elder, 2013–this issue) include chert, altered basalt, and serpentinite (SFPCLF01, SFPCLF02A, SFPCLF04.1). The altered basalt is from Point Bonita and contains hypersthene, basaltic hornblende, and chert-like cryptocrystalline grains. Outcrops from Montara Mountain and Point Reyes (SFPCLF05A, SFPCLF06, SFPCLF07) are granitic rocks of the Salinian Block and contain micas (biotite and chlorite), and hornblende along with minor epidote and zircon. The Salinian Block is considered a part of the Sierra Nevada displaced by the San Andreas fault (Fig. 4C; Elder, 2013–this issue).

5.2. Heavy mineral analysis of stream, beach, and seafloor sediment

For source provenance, samples from the Sacramento and San Joaquin Rivers and 11 other streams were analyzed for heavy minerals. Forty-eight seafloor and eight beach sites were examined to identify depositional provinces. To expand the data footprint, the seafloor samples include three from the Gulf of the Farallones collected in 1989 (Wong, 2001) and the stream samples include one from the Russian River collected in 1981 (Wong and Klise, 1986). Seventy-four samples were analyzed by point counting (Apx. 1). Many other beach samples were too coarse-grained to yield recognizable heavy minerals in the useable grain size fraction, while other samples from bays or shallows off the main channels were too fine-grained.

The heavy minerals in the 2- to 4-phi (0.25 to 0.063 mm) sand fraction range from less than 0.1 to 99% by weight, with an average of 84%. The actual number of nonopaque grains available for examination varies as the number of opaque grains or otherwise unidentifiable grains are encountered. As many as 600 grains were counted to accumulate at least 200 nonopaque grains; the average count was 372 grains. Eight samples yielded fewer than 200 nonopaque grains but have been retained in the analysis because the sample locations are not otherwise represented (Apx. 1).

The nonopaque heavy minerals in the sediment are dominated by amphiboles and pyroxenes (Apx. 1). The amphibole group includes brown or green hornblende, basaltic hornblende, glaucophane, and undifferentiated blue–green amphibole. Pyroxene varieties include hypersthene, enstatite, and augite or other clinopyroxenes. Less abundant but commonly occurring minerals include epidote varieties epidote and zoisite, sphene, zircon, and garnet, and — not usually appearing with heavy minerals — carbonate and chert. Carbonate grains are probably aragonite (sp. g. 2.94–2.95) from organic shell material. Grains of chert, a cryptocrystalline silica rock fragment, survive the heavy mineral separation because iron oxide either coats or is disseminated throughout the grains.

Abundance maps for selected minerals provide an overview of mineral distribution in the San Francisco Bay Coastal System (Fig. 2). Hornblende and hypersthene readily trace the Sierran sediment from the Central Valley to the coast, but are present in almost all samples. West of Carquinez Strait, glaucophane, garnet, and chert — contributions from Franciscan terranes — are more abundant. Zircon, a common detrital mineral, is not especially diagnostic for Sierran or Franciscan sediment.

For a statistical determination of the path of heavy minerals in the study area, we have applied a Bray–Curtis cluster analysis with a square-root transform (Clarke and Gorley, 2006). The graphic product of this analysis is a dendrogram that groups samples by mineralogic similarity (Fig. 3). Classes and subclasses were selected from branches of the dendrogram and numbered starting from the highest level of similarity (~70) and adjacency (attached to the same higher branch) to the lowest (~50).

Class 1 includes 32 of the 74 samples and could be subdivided into three subclasses 1.1, 1.2, and 1.3. Class 2 consists of 4 samples and class 3 consists of 20 samples with two subclasses 3.1 and 3.2. The remaining samples occupy progressively more dissimilar classes numbered 4 to 9 and consist of two to four samples each; one sample is assigned to class 10 for reference in this discussion. Mean values for each class of mineral abundance (as percent of nonopaque grains) for the most commonly occurring minerals are compiled in Table 3. Though mean values are provided for the smaller classes, there is great variability in actual values among members of class 4 and higher.

In the following discussion, percent abundances prefaced by “M” are mean values, “hornblende” refers to combined green and brown hornblende, “clinopyroxene” refers to combined augite and other clinopyroxene, and “epidote” refers to combined epidote and zoisite. Seafloor samples refer to those collected from the top 10 cm below the water bottom, whether inside or outside the Bay. Since all the available heavy mineral data, whether seafloor, beach, stream, or outcrop, were input for the cluster analysis, the resulting classes include mixes of the types of samples. As possible sediment sources, the classes consisting primarily of stream samples are described first, followed by seafloor and beach classes.

Table 2
Description of outcrop samples from selected locations in San Francisco area.

Sample	Description	Geologic unit	Mineralogy
SFPCLF01	Red radiolarian chert; Alexander Ave section, turnout just to the east of hwy 101, north end of Golden Gate Bridge	Franciscan Complex, Marin Headlands terrane	Chert
SFPCLF02A	Altered basalt, Pt. Bonita	Franciscan Complex, Marin Headlands terrane	Hypersthene, basaltic hornblende, ?chert (cryptocrystalline rock fragments)
SFPCLF04.1	Serpentinite; south of Fort Point, southern end of Golden Gate Bridge	Franciscan Complex, Marin Headlands terrane	Serpentine
SFPCLF05A	Granitic; Montara Mtn.	Salinian Block	Chlorite, minor hornblende
SFPCLF06	Granitic; Point Reyes	Salinian Block	Chlorite, biotite
SFPCLF07	Granitic, altered; Point Reyes	Salinian Block	Biotite, epidote, zircon
SFPCLF09	Sandstone outcrop, Ocean Beach, southwest San Francisco	?Merced Formation	See class 3.1 (Table 3)

5.3. Stream mineral classes

Class 2 consists of four samples taken from streams that empty into Central Bay and South Bay. They have in common moderate amounts of hornblende and hypersthene, glaucophane, zircon, and garnet (Tables 1, 3). Compared to mean values for the class, the actual mineral abundances are variable: Wildcat Creek has almost 16% and Alameda Creek 7% glaucophane, whereas the Marin County streams contain less than 2% glaucophane. These samples are from watersheds in primarily Franciscan Complex rocks. Wildcat Creek and Alameda Creek also draw from exposures of Great Valley sedimentary rocks and serpentinite exposures (Elder, 2013–this issue).

Class 5 consists of three stream samples that contain similar amounts of enstatite, clinopyroxene, and chert (Table 3). The samples are from Sonoma Creek and Napa River near San Pablo Bay and from San Francisquito Creek in South Bay (Fig. 4C). Among the three samples, Sonoma Creek is distinguished by a larger amount of glaucophane (3.5%), probably from the exposures of Franciscan Complex in the watershed. The Napa River drains a mix of the Great Valley, Franciscan

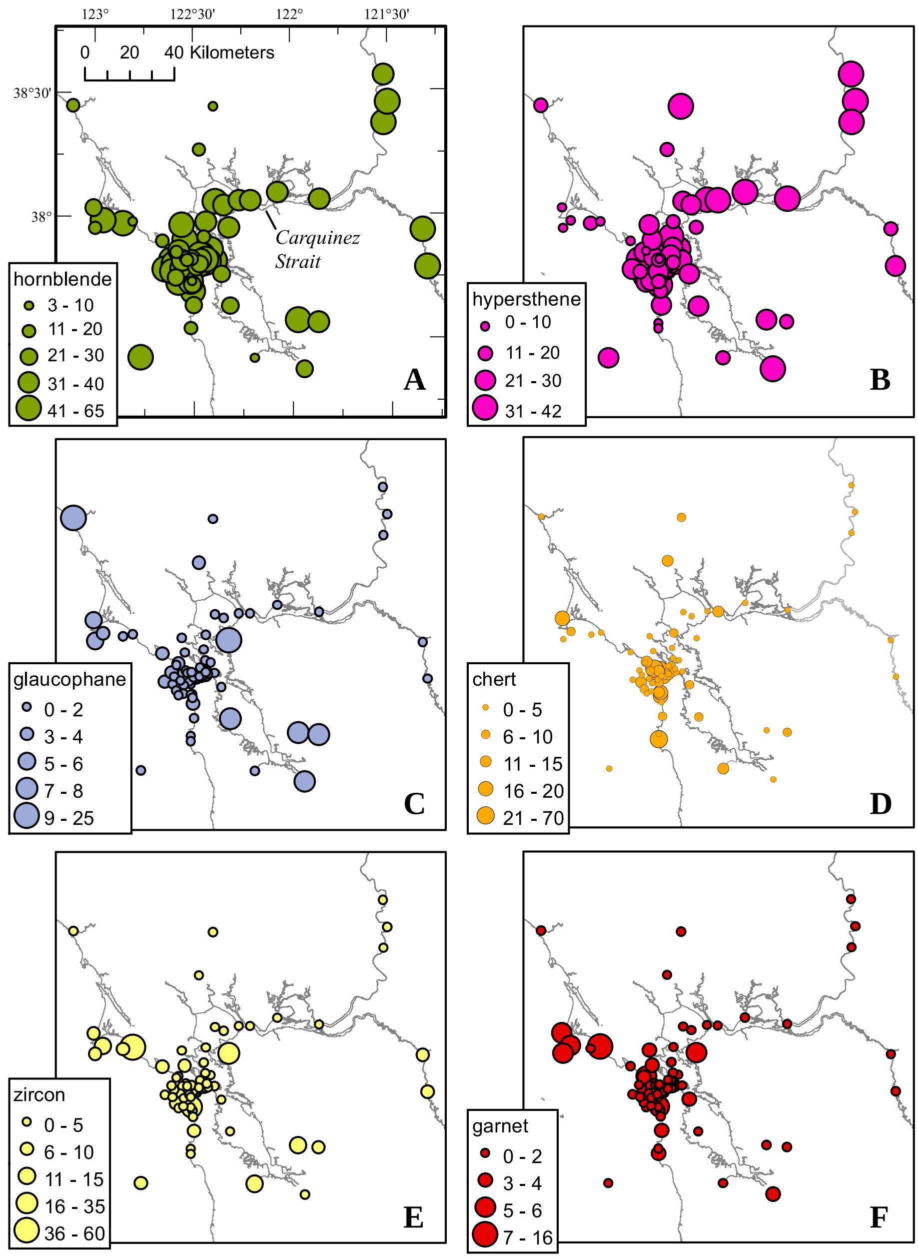


Fig. 2. Abundance of selected heavy minerals. *A.* Hornblende and *B.* hypersthene are typical of sediment from the Sierra Nevada. *C.* Glaucophane, *D.* chert, and *E.* garnet can be attributed to the Franciscan Complex terranes, which appear in the sediment stream west of Carquinez Strait (CS). *F.* Zircon abundance is not especially tied to either type of sediment.

Complex, and Sonoma Volcanics, but the abundance of hypersthene (twice as much as the other two samples) strongly identifies the sample with the volcanic rocks. In contrast, San Francisquito Creek is distinguished by a large amount of zircon (11%).

Class 6 consists of samples with elevated glaucophane and moderate amounts of hornblende, clinopyroxene and epidote in common (Fig. 4C, Table 3). One sample, from the Guadalupe River draining into South Bay, has about twice as much hypersthene (39%) and more augite, sphene, and garnet than the other two samples. By mineral content and geographic location, this sample should probably be grouped with class 2 or class 5.

The remaining two samples were from previous studies that were re-analyzed with the samples in the current data set for comparison. One is a seafloor sample (F2_G97) collected from about 4.5 km south of Point Reyes (Wong, 2001) and the other is a sample from the Russian River (RR_VV2; Wong and Klise, 1986). The Russian River sample has about 24% glaucophane compared to 5% off Point Reyes, hence, the Russian River is a very likely source for the offshore sample.

Except for the Russian River, the stream samples described in these classes were taken from watersheds that drain into San Francisco Bay west of Carquinez Strait. Almost all include Franciscan Complex lithologies (Table 1; Elder, 2013–this issue) and carry similar minerals in varying amounts that might not be unique identifiers. The largest streams in the San Francisco Bay Coastal System are the Sacramento and San Joaquin Rivers, which are discussed with the closely related seafloor and beach samples in the following section.

5.4. Seafloor and beach sediment classes

5.4.1. Class 1 — Sierran

Class 1 samples occupy the main channel through the San Francisco Bay Coastal System from the Sacramento and San Joaquin Rivers to the

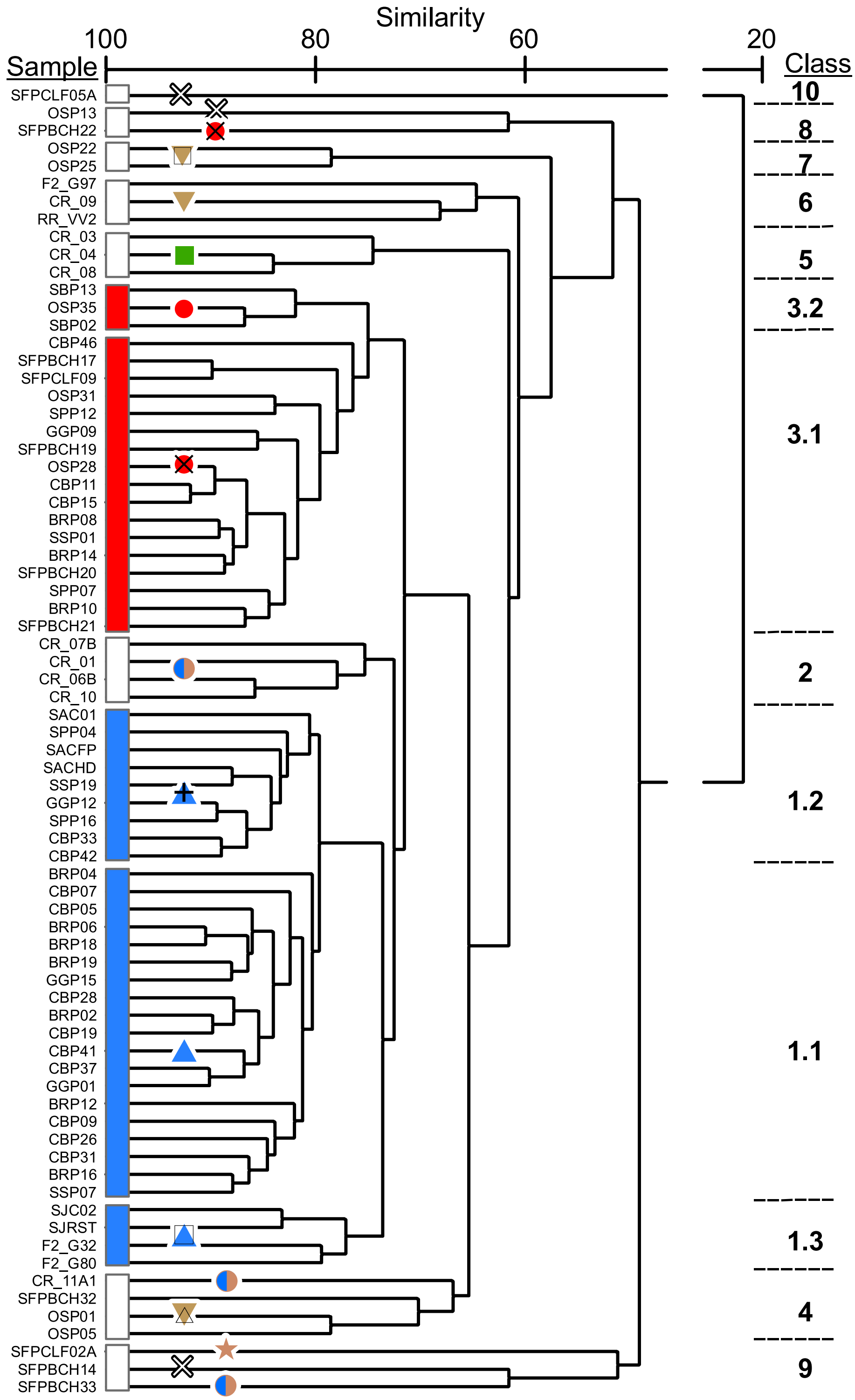


Fig. 3. Dendrogram of classes of similar samples identified by cluster analysis. The dendrogram similarity axis is discontinuous between 25 and 45. The classes (1.x and 3.x) highlighted by shading include samples from the Sacramento and San Joaquin Rivers and all the seafloor samples from the confluence of those rivers through the Golden Gate to the San Francisco Bar and southern offshore areas. The remaining samples fall into small classes (2 and 4–10), which include stream samples and outcrops. Classes are described in Table 1 and plotted in Fig. 4. Some samples have been reclassified as described in the text.

San Francisco Bar. Three subclasses (also labeled "class" for brevity) are discernible from the cluster analysis. Table 3 lists average abundances of major minerals for each subclass 1.1, 1.2, and 1.3 and for the parent class 1.

Class 1.1 consists of 19 samples with abundant hornblende (M 43%), hypersthene (M 30%), and a mean of 5% or less of other minerals (Table 3). Except for one sample located in Suisun Bay, class 1.1 samples are concentrated between west Central Bay and the San Francisco Bar (Fig. 4A). This category consists only of seafloor samples.

Class 1.2 consists of three samples from the Sacramento River and six seafloor samples between the river and the Golden Gate, so this category spans the whole coastal system from Central Valley to the

Table 3
Average percent abundance of most common minerals or mineral groups in each heavy mineral class.

Class	spl cnt	hb, gn-bn	hb, bas	amph, bg	Glaucophane	Hypersthene	Enstatite	cpx	Epidote	Sphene	Zircon	Garnet	Chert	Chlorite	CO_3	Description
1	32	43	4	4	1	30	3	2	5	3	2	1	0	0	0	See subclass detail below.
2	4	35	6	2	6	19	4	1	6	4	11	3	1	0	0	Creeks: Corte Madera, Del Presidio, Wildcat, Alameda
3	20	27	5	10	1	25	5	5	4	3	2	1	9	0	0	See subclass detail below.
4	4	28	4	5	4	9	4	8	6	5	7	4	12	0	1	seafloor Point Reyes (2), Muir Beach (1), Calaveras Creek (1)
5	3	7	2	2	2	20	23	19	4	2	5	1	10	0	0	Sonoma Creek, Napa River, San Francisquito Creek
6	3	17	3	0	12	19	1	8	6	6	3	3	0	0	1	Guadalupe River, seafloor Point Reyes (GOF), Russian River
7	2	14	2	35	2	16	0	23	0	1	4	2	0	0	1	Seafloor west Marin County
8	2	3	2	0	1	10	1	1	6	9	44	10	8	0	2	Seafloor west Marin County, SF Ocean Beach
9	3	11	3	3	0	15	2	2	0	3	0	1	56	0	0	Beach off Montara Mtn., Point Bonita outcrop, Bonita Cove beach
10	1	1	0	0	0	2	0	0	0	3	0	0	1	91	0	Montara Mountain outcrop
Subclasses 1.x and 3.x																
1.1	19	43	4	4	1	30	5	1	4	4	1	1	1	0	0	West Central Bay, SF Bar; Suisun Bay (1); seafloor samples
1.2	9	39	5	3	1	35	1	5	7	2	1	1	0	0	0	Sacramento River to SF Bar; stream or seafloor samples
1.3	4	51	4	4	1	17	0	2	3	3	6	1	0	0	0	San Joaquin River (2); Gulf of the Farallones (2)
3.1	17	28	5	10	1	26	6	3	4	3	2	1	9	0	0	Carquinez Strait to SF Bar, south coast; seafloor and beach samples
3.2	3	22	3	7	2	24	0	15	5	4	5	3	7	0	0	Seafloor South Bay (2), Pacifica (1)
Min		1	0	0	0	0	0	0	0	0	0	0	0	0	0	Of all 74 samples
Max		59	10	38	24	42	25	30	15	14	56	15	69	91	5	Of all 74 samples
Mean		31	4	6	2	24	4	5	4	3	4	1	6	1	0	Of all 74 samples
Std		14	2	7	4	10	5	6	3	3	8	2	12	11	1	Of all 74 samples

Abbreviations: "spl cnt" — number of samples; "hb,gn-brn" — green or brown hornblende; "hb, bas" — basaltic hornblende; "amph, bg" — blue–green amphibole; "cpx" — augite and other clinopyroxene; "CO_3" — carbonate. Values are percent of nonopaque grains averaged over sample count for each class.
Description: "seafloor" — samples collected from bay floor or seafloor; stream samples collected from banks or mid-stream (Sacramento, San Joaquin Rivers) have "River" or "Creek" in feature name; beach samples collected onshore; outcrop samples are also referred to as cliff samples; GOF is Gulf of the Farallones; where present under "Description", (n) is the number samples of a subgroup in the class.

Gate. Class 1.2 is similar to class 1.1, but contains less hornblende (M 39%), more hypersthene (M 35%), and slightly more epidote (Table 3).

Class 1.3 consists of two samples from the San Joaquin River and two from the Gulf of the Farallones (Table 3, Fig. 4A). The four samples have similar abundances of hypersthene, enstatite, and augite, but Gulf samples have less hornblende, more glaucophane, half as much sphene, and significantly more zircon than the San Joaquin River samples. Compared to the samples from the Sacramento River (class 1.2), the San Joaquin River samples contain more hornblende (57–59%), less hypersthene (10–20%), and more zircon (6–8%). Unlike the continuity of class 1.2 sediment, the San Joaquin mineralogy is not apparent west of the confluence of the two rivers. The samples from the Gulf of the Farallones may qualify as a similar but separate subclass.

Class 1 provides a continuous trace of Sacramento–San Joaquin sediment from the source streams in the Central Valley to the coast and shelf that can be identified as Sierran. The subclasses differentiate between the Sacramento and San Joaquin sediments, highlight the cluster around the Golden Gate, and identify a tentative relationship to samples out on the shelf in the Gulf of the Farallones.

5.4.2. Class 3 — West Bay and South Coast

Class 3.1 consists of one bedrock, four beach, and 12 seafloor samples with moderate amounts of hornblende (M 28%) and hypersthene (M 26%), and more blue–green amphibole (M 10%) and chert (M 9%) than class 1 samples. Samples of class 3.1 lie between Carquinez Strait and the San Francisco Bar occupying most of the same area as class 1.1, but extend further west to include beach samples and one cliff outcrop sample (SFPCLF09) on the southern outer coast (Fig. 4A, C).

The three samples grouped as class 3.2 are dissimilar in minor mineral abundance (Table 3, Fig. 4A). Two samples are from South Bay and one is from offshore Pacifica. The northernmost South Bay sample is more similar to the outer coast sample than to the other South Bay sample, which has a large amount of glaucophane (6%) compared to only trace amounts in the other two samples. The Pacifica and northern South Bay sample may be samples that diverged from the main stream of class 3.1 samples in Central Bay. The more southerly sample from South Bay may be receiving sediment from the adjoining San Francisco Peninsula watershed, which drains Franciscan terrane.

Class 3 samples appear west of Carquinez Strait and are intermingled with class 1 samples from there to the San Francisco Bar. Unlike class 1 samples, class 3 samples make incursions into South Bay and occur farther south on the outer coast. The chert content of class 3 indicates that the samples include contributions from Franciscan terranes that nearby class 1 samples do not have (Table 3). The sediment on the Bay floor is not homogeneous even in the confined Golden Gate area (Fig. 4B).

5.4.3. Classes 4 and 7 — North Coast Franciscan

Class 4 consists of two seafloor samples (OSP01 and OSP05) from either side of Point Reyes, one beach sample from Muir Beach (southwestern Marin, SFPBCH32), and one stream sample from Calaveras Creek in South Bay. This class is characterized by moderate amounts of hornblende, glaucophane and chert (Table 3; Fig 4A). Except for those heavy mineral grain types, the Calaveras Creek sample could be separated from this class because it contains more hypersthene, glaucophane, and sphene and is geographically distant (Fig. 4C).

The Muir Beach sample is unlike the Point Reyes samples because it lacks clinopyroxene, has less zircon and garnet, and has a significant amount (4%) of carbonate fragments. As borne out by their positions in the dendrogram, the two Point Reyes samples are similar to each other but far less so to the samples from Muir Beach or Calaveras Creek (Fig. 3).

Class 7 consists of two samples (OSP22 and OSP25) from the seafloor off Stinson and Muir Beaches in southwest Marin County (Fig. 4A; Table 3). These contain abundant blue–green amphibole (M 35%), which might include actinolite, and augite (M 7%) and are depleted in hornblende (M 14%) and hypersthene (M 16%). The seafloor sample taken about 1 km offshore of Muir Beach has similar mineralogy to the Muir Beach sample, but the abundances are different.

Classes 4 and 7 have Franciscan mineralogy and, excluding the sample from Calaveras Creek, characterize the inner coast north of the Golden Gate. The sample from Calaveras Creek is better grouped with Alameda Creek on the basis of its mineralogy and location as an upstream feeder to Alameda Creek.

5.4.4. Outliers

Classes 8 through 10, which are the most dissimilar on the dendrogram (Fig. 2) are collections of samples with little in common. Setting the class assignments aside, we describe the individual outliers and propose alternate class placements. The two coastal cliff outcrop samples, SFPCLF02A from Point Bonita and SFPCLF05A from Montara Mountain, have been described earlier (Table 2). Sample OSP13 from eastern Drakes Bay is overwhelmed by zircon (56%), garnet (15%) and carbonate fragments (5%), with little hornblende or hypersthene. The sample lies 0.5 km offshore of Tertiary sediments overlying Salinian granitic rocks. Though unlike the Salinian outcrop mineralogy, we categorize this as Salinian-derived sediment by location.

Sample SFPBCH22 is from Ocean Beach and is characterized by 20% hypersthene, 14% sphene, 32% zircon, 6% garnet, and 15% chert (Table 3, Fig. 4C). By location it should be a member of class 3.2, but it contains far less hornblende than the neighboring class 3.2 samples.

Sample SFPBCH33, a beach sample from Bonita Cove on the Marin side of the Golden Gate has 7% hypersthene, 7% enstatite, minor epidote and sphene, and 69% chert not much like the nearby Point Bonita altered basalt sample. The abundance of chert and location at the base of the Marin Headlands supports classification as Franciscan.

The southernmost outlier is a beach sample SFPBCH14 from Montara State Beach below Montara Mountain. The sample is mainly chert-like cryptocrystalline grains accompanied by small amounts of hornblende, hypersthene, and enstatite. We place this with Salinian-derived sediment.

6. Discussion

The heavy mineralogy of the San Francisco Coastal System has been described from previous studies, but deserves a revisit to provide a uniform data set for the specific collection of samples from this provenance and transport study. Heavy mineral samples in previous studies often addressed the 2–4 phi size fraction, but both smaller and larger intervals were used (Cherry, 1966; Hall, 1965; Minard, 1964; Moore, 1965; Schatz, 1963). Many of these previous studies calculated mineral abundance on the basis of 100 nonopaque grains, whereas the current study sought to identify at least 200 nonopaque grains where available to bolster the reliability of the mineral statistics (Galehouse, 1971).

Our analysis provides a uniform set of data to compare the source geology with the sand-sized sediment making its way to beaches on the open coast. We detail our findings for the interior of San Francisco Bay and the environments outside the Golden Gate.

6.1. Interior San Francisco Bay

Sand-sized surficial sediment that we classify as Sierran can be traced from the Sacramento and San Joaquin Rivers westward through Carquinez Strait to North Bay, Central Bay, the Golden Gate and out to the San Francisco Bar. From the confluence of the two rivers to Carquinez Strait the sediment (class 1.2) matches that from the Sacramento River. West of Carquinez Strait through Central Bay and the Golden Gate there are still samples that are purely Sierran (class 1.2), but these are intermingled with samples (class 3) that, while still exhibiting Sierran mineralogy, have minor contributions from watersheds that are underlain by the Franciscan Complex (chert) and Sonoma Volcanics (hypersthene). Class 3 extends the Sierran sediment outside the Golden Gate across the San Francisco Bar to the south, including beach and offshore samples. An offshoot of class 3 samples to South Bay has a slightly different character that might indicate contributions from South Bay Franciscan exposures (Fig. 4A).

The intermingling of class 1 and 3 samples, especially at the Golden Gate is unexpected because the constriction of the area should encourage homogeneous samples (Fig. 4B). In this same area other studies have detected net bayward sediment transport along the northern coast of San Francisco (Barnard et al., 2013a–this issue), but the heavy mineral data do not indicate any directionality.

Based on heavy mineralogy, sand-size sediment from local water sheds that drain into San Francisco Bay make a barely detectable contribution to the surficial sediment. Napa Creek and Sonoma Creek drain valleys in the Sonoma Volcanics, from which hypersthene is a likely component accounting for part of the difference in the mineralogy west of Carquinez Strait. Current grain size data do not show much sand-size sediment crossing San Pablo Bay to the main channel. Corte Madera Creek and Del Presidio Creek in Marin County and Wildcat Creek in East Bay drain Franciscan Complex lithologies on either side of Central Bay, but there is no great increase in glaucophane past the mouth of glaucophane-rich Wildcat Creek. Sediment from Alameda Creek, Guadalupe River, and San Francisquito Creek, which drain into South Bay could supply some of the Franciscan Complex minerals that appear in the southernmost South Bay sample, yet, as in the case of San Pablo Bay, not much sand-size sediment crosses the mud flats to feed the main channel from South Bay.

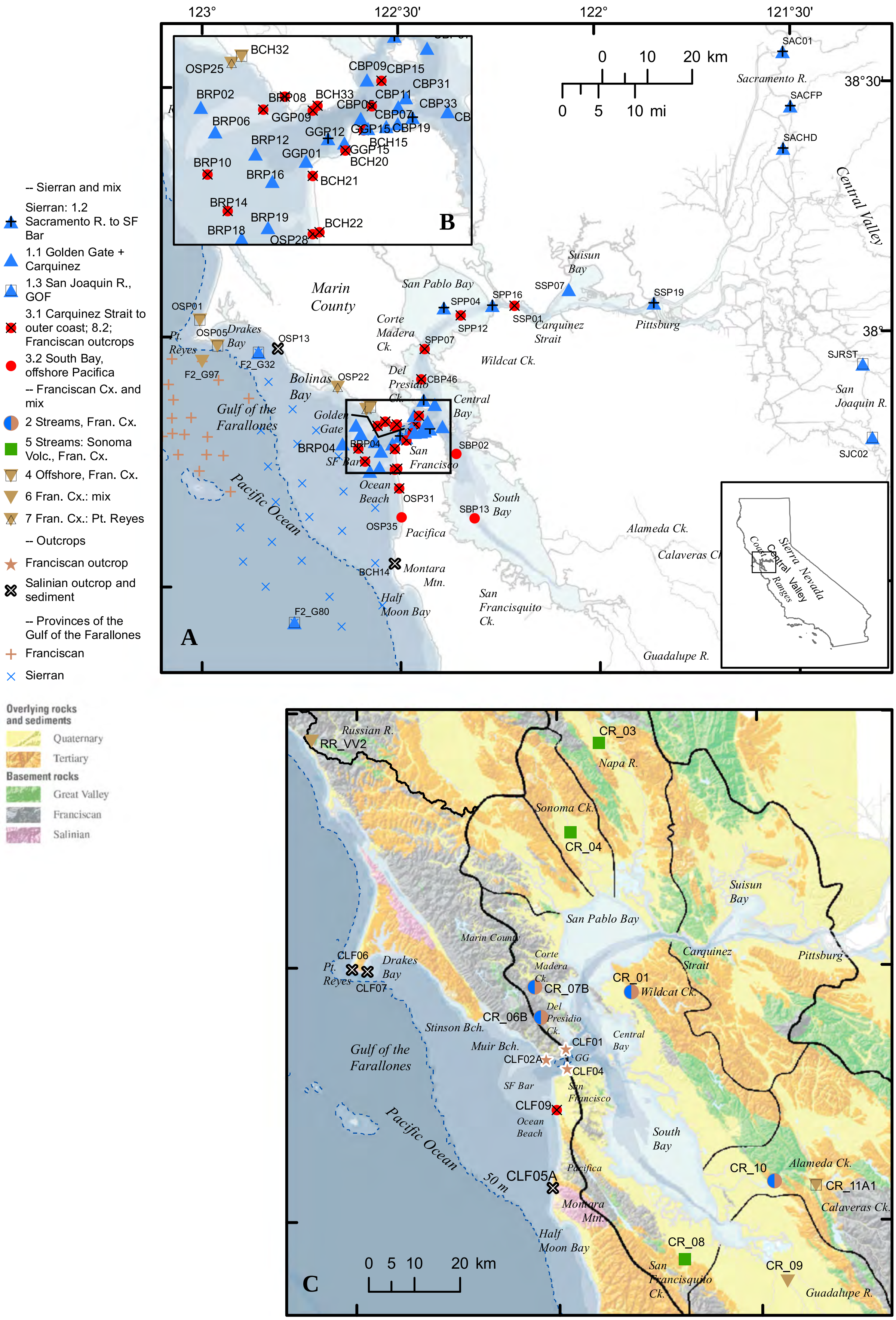
Since the presence of chert is one of the main discriminants between class 1 and class 3, we may need to look to the exposures of chert eroding from rocks and islands in the channel. The chert outcrop sample (SFPCLF01) included in this study is valuable as a type example of material that is very common around and in the Bay. Similarly, the serpentinite sample (SFPCLF04.1) serves as a type sample, but the locations of both samples are not unique.

6.2. Outside the Golden Gate

Barnard et al. (2013b–this issue) trace Sierran sediment beyond the San Francisco Bar to the inner continental shelf or the Gulf of the Farallones. The inclusion in this heavy mineral analysis of samples from a previous study extends the footprint of Sierran sediment to a depositional province on the Gulf of the Farallones (Wong, 2001; Fig. 4A). The Gulf Sierran province starts as a narrow north–south arm south of Drakes Bay, skirts the San Francisco Bar and widens southward to Half Moon Bay.

Though the previous work left unresolved whether the Farallones sediment may be relic from a previous lower sea level or is more recent sediment, the Sierra still appears to be the primary source. The Sierran heavy minerals of the Gulf are more like the Sierran sediment from within the Bay than the Salinian outcrop or sediment samples from this current study.

Our study area north of the San Francisco Bar starts at the Russian River mouth. North Coast Franciscan sediments discharged from the Russian River can be tracked southward to wrap around the Point Reyes peninsula, which is otherwise a dominantly Salinian granitic terrane.



123°
122°30'
122°
121°30'
38°30'
38°
0 10 20 km
0 5 10 mi
-- Sierran and mix
Sierran: 1.2 Sacramento R. to SF Bar
1.1 Golden Gate + Carquinez
1.3 San Joaquin R., GOF
3.1 Carquinez Strait to outer coast; 8.2; Franciscan outcrops
3.2 South Bay, offshore Pacifica
-- Franciscan Cx. and mix
2 Streams, Fran. Cx.
5 Streams: Sonoma Volc., Fran. Cx.
4 Offshore, Fran. Cx.
6 Fran. Cx.: mix
7 Fran. Cx.: Pt. Reyes
-- Outcrops
Franciscan outcrop
Salinian outcrop and sediment
-- Provinces of the Gulf of the Farallones
Franciscan
Sierran
A
B
C
BCH32
OSP25
CBP09
CBP15
CBP31
BRP02
BRP08
BCH33
CBP11
CBP05
CBP33
GGP09
CBP07
BRP06
GGP12
GGP15
CBP19
BRP12
BCH15
GGP01
GGP15
BRP10
BCH20
BRP16
BCH21
BRP14
BRP19
BCH22
BRP18
OSP28
SAC01
Sacramento R.
SACFP
SACHD
Central Valley
Suisun Bay
San Pablo Bay
SSP07
SPP16
SSP19
Marin County
SPP04
SSP01
Pittsburg
OSP01
Corte Madera Ck.
SPP12
Carquinez Strait
OSP05
Drakes Bay
OSP13
SPP07
Pt. Reyes
Wildcat Ck.
F2_G32
SJRST
F2_G97
Bolinas Bay
OSP22
Del Presidio Ck.
CBP46
San Joaquin R.
Central Bay
Gulf of the Farallones
Golden Gate
BRP04
San Francisco
SBP02
SJC02
SF Bar
Pacific Ocean
Ocean Beach
OSP31
South Bay
SBP13
OSP35
Pacifica
Alameda Ck.
Calaveras Ck.
BCH14
Montara Mtn.
Half Moon Bay
San Francisquito Ck.
F2_G80
Guadalupe R.
Coast Ranges
Central Valley
Sierra Nevada
Overlying rocks and sediments
Quaternary
Tertiary
Basement rocks
Great Valley
Franciscan
Salinian
Russian R.
RR_VV2
CR_03
Napa R.
Sonoma Ck.
CR_04
Suisun Bay
San Pablo Bay
Marin County
Carquinez Strait
Pittsburg
Corte Madera Ck.
CLF06
Drakes Bay
Pt. Reyes
CLF07
CR_07B
CR_01
Wildcat Ck.
CR_06B
Del Presidio Ck.
Stinson Bch.
CLF01
Central Bay
Muir Bch.
CLF02A
GG
CLF04
Gulf of the Farallones
SF Bar
San Francisco
CLF09
Ocean Beach
South Bay
Pacific Ocean
CR_10
Alameda Ck.
Pacifica
CLF05A
CR_11A1
50 m
Calaveras Ck.
Montara Mtn.
Half Moon Bay
CR_08
San Francisquito Ck.
CR_09
Guadalupe R.
0 5 10 20 km

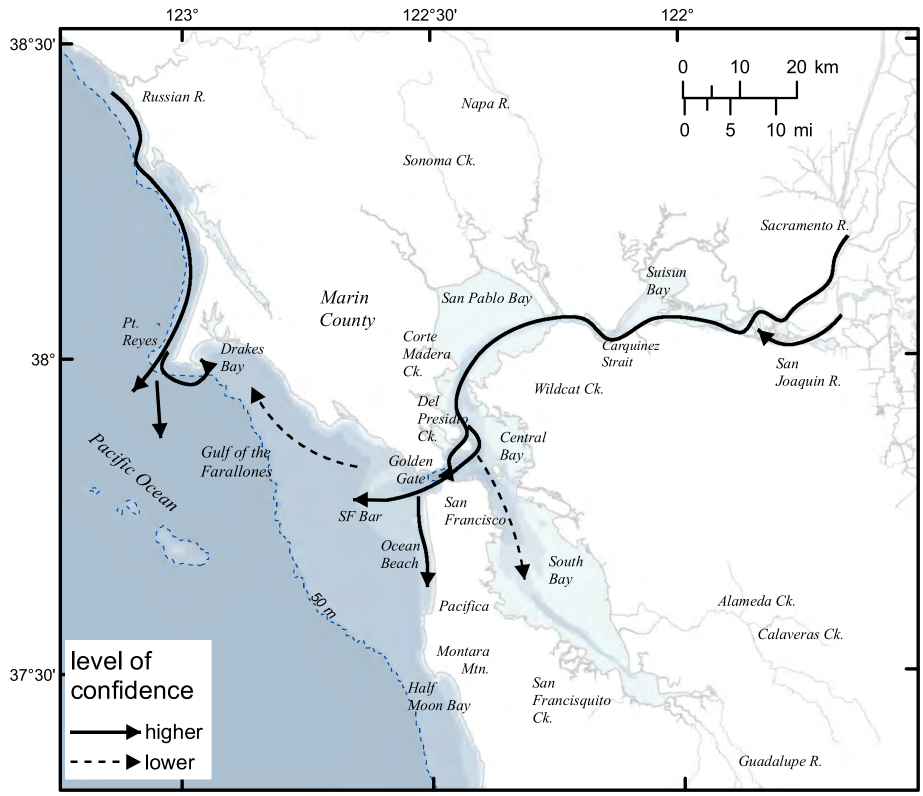


Fig. 5. Transport directions in the San Francisco Bay Coastal System inferred from heavy mineral distributions.

Opposite Point Reyes on the east side of Drakes Bay a near-offshore sample (OSP13) contains no Franciscan minerals. Off southwest Marin County, where Franciscan Complex exposures reappear along the coast, beach and offshore samples have related Franciscan mineralogy, but the mineral abundances are unlike that which appears around Point Reyes.

A Franciscan province was also defined in the Gulf of the Farallones (Wong, 2001). A sample (F2_G97) from that province that was re-analyzed in this study ties the Franciscan sediment transported from the Russian River to the Franciscan province that extends west and south of Point Reyes (Fig. 4A). The eastern extent of the Franciscan sediment in Drakes Bay is bordered by the north arm of the Gulf Sierran province, so any Franciscan sediment from around Point Reyes is unrelated to Franciscan sediment off southwest Marin County north of the San Francisco Bar.

6.3. Review of method

The analysis of heavy minerals in surficial sediment in the San Francisco Bay Coastal System has identified the Sacramento River as the primary source of sand-sized sediment that ends up as beach sand on the San Francisco coast or is dispersed into the Gulf of the Farallones. The useable grain size of this analysis excluded many of the coarse-grained beach samples from both inside and outside the Bay and created undercounts in some other samples (Apx. 1). The analysis of these coarser samples would have to depend on another method. Similarly, the fine-grained samples are not accessible by this method, but they do not contribute to the beach sand.

The cluster analysis covered about 60% of the variability in the data set and worked best with just the populous Sierran classes. A future analysis may have to include a geographic factor to avoid the mislocation of nearby and similar samples.

The prevalence of similar heavy minerals from the watersheds local to San Francisco Bay reduce the ability to discern source from any specific one. A spike in abundance of hypersthene and augite from the Sonoma or Napa watersheds would point to them as sources, but this is not the case in the samples from the main channel fronting San Pablo Bay.

The outcrop samples were only valuable for qualitative mineral identification. Except for the type samples of chert and serpentinite, to which we could assign close to 90% of grain type, it is not clear that one handful of outcrop will have a typical heavy mineralogy.

7. Conclusions

Transport vectors for the San Francisco Bay Coastal System based on heavy minerals are portrayed in Fig. 5. A higher level of confidence is applied to those paths supported by mineral continuity. The lower level of confidence is applied to paths with directional uncertainty or with lower sample density, as in the shelf beyond the San Francisco Bar.

Fig. 4. Map of heavy mineral classes determined by cluster analysis. "SFP" dropped from sample labels for brevity. *A.* Location of seafloor and beach samples partitioned between predominantly Sierran (from Sacramento and San Joaquin Rivers) and Franciscan classes. Included are sample analyses from the Gulf of the Farallones (Wong, 2001) from which three samples were re-analyzed. *B.* Enlargement of sample locations at the Golden Gate and San Francisco Bar. *C.* Geologic setting of stream and outcrop samples. Streams include those that drain into San Francisco Bay and the Russian River (in Franciscan Complex) on the coast to the north. Outcrop samples were collected on either side of the Golden Gate, at Point Reyes and at Montara Mountain. Geologic base map from Graymer and others (2006). Watersheds delineated by Elder (2013–this issue).

Heavy minerals in sand-sized surficial sediment clearly trace a path from the Sacramento River to the San Francisco Bar (Fig. 5) pointing to the Sacramento River and sources in the Sierra Nevada as the likely primary source of sediment for the whole system. This distribution supports dominant transport directions that have been defined by bedform asymmetry (Barnard et al., 2013a–this issue), but no absolute directional trend is evident in either the abundance of the individual minerals or the weighting from the cluster analysis. No small local streams entering the Bay appear to contribute much to the current sediment population. Sediment is contributed from the San Joaquin River, but not enough to change the composition of the Sacramento-dominated sediment east of Carquinez Strait.

Sediment is clearly leaving through the Golden Gate and fanning out from the San Francisco Bar westward towards the Gulf of the Farallones and southward along the coast of the San Francisco Peninsula. Though nearshore samples support southeastward flow of Franciscan sediment from southwestern Marin County, Franciscan sediment disappears in the Sierran province of the Gulf within 5 km offshore.

The Russian River, a large watershed on the California coast north of the San Francisco area, was included in this study as a possible source of beach sand to the San Francisco Bar area. Sand-sized sediment from the Russian River moves south to Point Reyes, spreads out west and south of the point and rounds the peninsula to spread partway across Drakes Bay. Franciscan sediment gives way to the shelf Sierran province, which expands southward opposite the Golden Gate.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.margeo.2013.05.012. These data include Google maps of the most important areas described in this article.

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Exhibit J

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Sand sources and transport pathways for the San Francisco Bay coastal system, based on X-ray diffraction mineralogy

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ABSTRACT

The mineralogical compositions of 119 samples collected from throughout the San Francisco Bay coastal system, including bayfloor and seafloor, area beaches, cliff outcrops, and major drainages, were determined using X-ray diffraction (XRD). Comparison of the mineral concentrations and application of statistical cluster analysis of XRD spectra allowed for the determination of provenances and transport pathways. The use of XRD mineral identifications provides semi-quantitative compositions needed for comparisons of beach and offshore sands with potential cliff and river sources, but the innovative cluster analysis of XRD diffraction spectra provides a unique visualization of how groups of samples within the San Francisco Bay coastal system are related so that sand-sized sediment transport pathways can be inferred.

The main vector for sediment transport as defined by the XRD analysis is from San Francisco Bay to the outer coast, where the sand then accumulates on the ebb tidal delta and also moves alongshore. This mineralogical link defines a critical pathway because large volumes of sediment have been removed from the Bay over the last century via channel dredging, aggregate mining, and borrow pit mining, with comparable volumes of erosion from the ebb tidal delta over the same period, in addition to high rates of shoreline retreat along the adjacent, open-coast beaches. Therefore, while previously only a temporal relationship was established, the transport pathway defined by mineralogical and geochemical tracers support the link between anthropogenic activities in the Bay and widespread erosion outside the Bay. The XRD results also establish the regional and local importance of sediment derived from cliff erosion, as well as both proximal and distal fluvial sources. This research is an important contribution to a broader provenance study aimed at identifying the driving forces for widespread geomorphic change in a heavily urbanized coastal-estuarine system.

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1. Introduction

Over 150 million m^3 of sand-sized sediment has been lost during the last half century from the central area of the San Francisco Bay (SF Bay) coastal system (Hanes and Barnard, 2007; Fregoso et al., 2008; Dallas and Barnard, 2009, 2011). Over the same time period, widespread erosion occurred on adjacent beaches, wetlands, and submarine deposits (Atwater et al., 1979; Hapke et al., 2006; Barnard and Kvitek, 2010; Dallas and Barnard, 2011; Barnard et al., 2012a, 2012b). These impacts to the outer coast may be the result of anthropogenic modifications within the system such as delta damming, sediment mining, offshore dredge disposal, and the restoration of salt ponds formerly surrounded by levees (e.g., Knowles and Cayan, 2004; Wright and Schoellhamer, 2004; Dallas and Barnard, 2011), but no direct linkages have previously been established.

The Golden Gate strait is the sole connection of SF Bay with the Pacific Ocean, where over 7.57 km^3 of water is transported daily along with mud, sand, biogenic material, and pollutants (McHugh, 2001). SF Bay and the adjacent ocean have typically been treated as separate entities. However, recent research documents the dynamic processes that occur at the mouth of SF Bay, which highlights the connection of physical processes between SF Bay and the adjacent coastal ocean (e.g., Barnard et al., 2007; Dallas and Barnard, 2011; Barnard et al., 2012b).

Sediment within the SF Bay coastal system is derived from diverse sources and undergoes complex transport and mixing processes. Sources range from rivers that erode the distal Sierra Nevada granitic and metamorphic rocks and feed into the two major rivers of the Great Valley (the Sacramento and San Joaquin Rivers), local watersheds draining the Pacific Coast Ranges that are composed of the heterogeneous Franciscan Complex, displaced Sierran granitic rocks, and Mesozoic and Cenozoic sedimentary rocks, and sediment transported alongshore in the coastal ocean (Gilbert, 1917; Yancey and Lee, 1972; Schlocker, 1974; Porterfield, 1980; Graymer et al., 2006).

X-ray diffraction mineralogy is used here to determine the characteristic minerals for each of the predominant source regions throughout the study area, including all major drainages and rock types. The mineralogical compositions of the source regions are then compared with those of the beach and seabed sands to provide estimates of mixing using statistical analyses. That information is further used to trace sources of

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sand-sized sediment deposited around the SF Bay coastal system and to infer dispersal pathways.

This mineralogical study is part of a multi-faceted, multi-disciplinary provenance study designed to establish the primary sources, sinks, and inferred transport pathways of sand in the region, and thereby establish links between anthropogenic activities and geomorphic change (Barnard et al., 2013-in this issue-a). The program is based on comprehensive sampling of sediment including the seabed, bayfloor, beaches, representative rock units, and all major and some minor drainages. Our approach is unique in using bulk XRD mineralogy of sand (a technique generally applied to finer size fractions) and cluster analyses of XRD spectra to determine these sources and transport pathways. Heavy minerals and isotopes are more typically used for this purpose.

2. Methods

2.1. Sample collection

The 119 samples analyzed are geographically representative of the SF Bay coastal system (Fig. 1). Beach sand was collected by hand scoop (n = 27), and seafloor/bayfloor samples (n = 61) at variable water depths by using a Smith–MaIntyre grab from which the surface 10 cm was subsampled. Source rock sampling (n = 18) followed the distribution of rock types displayed on a geological map of the area; rock types representative of all formations in the area were sampled (chert, basalt, various types of sandstone, serpentinite, and granitic rocks displaying various stages of weathering) from outcrops near beach sand locations along the coast. Streambed sediments (n = 13) were collected by hand scoop along the water's edge, with the exception of the Sacramento and San Joaquin Rivers, where several were collected by boat in the center of the channel.

2.2. Analytical techniques

All sediment sample analyses were performed on a consistent size fraction, 0.15–0.5 mm (mean D_{10}–D_{90} range of outer coast beach samples), after the shell was removed by weak hydrochloric acid leach. Potential source rocks were analyzed in bulk. All samples were ground in a McCrone micronizing mill with 4 ml of methanol for 5 min. The powder was then dried at 80 °C overnight, and was further ground with a

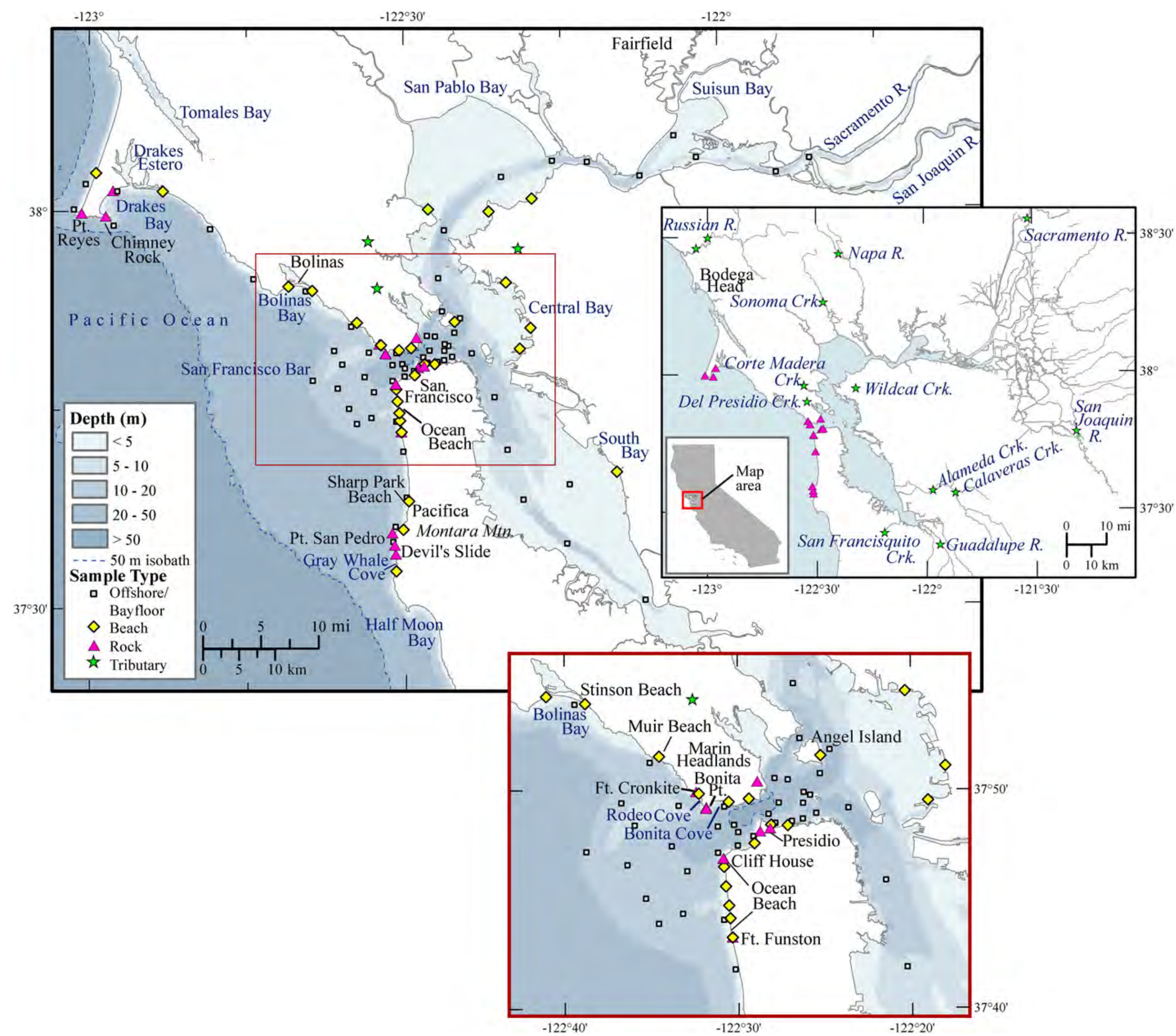

Fig. 1. Map showing all sample locations used in this study as well as water depth.

mortar and pestle to fit through a 106 μm sieve and back-packed into an aluminum sample holder to ensure randomization. Samples were analyzed using a Philips XRD with graphite monochromator at 40 kV and 45 mA. Step scans were run from 5° to 65° 2θ with 0.02° steps, using CuKα radiation and a count time of 2 s/step.

XRD digital scan data were analyzed using Philips X'Pert High Score software's search and match function to identify peaks and mineral composition. Semi-quantitative mineral percentages were determined by multiplying unique peak intensities for each mineral in a sample by relative intensity factors as described by Cook et al. (1975) and the products for all minerals in a sample were then summed to 100%. Intensity factors were estimated for minerals not found in Cook et al. (1975) by utilizing values for minerals within the same mineral group. Ten percent of the samples were run in duplicate to test precision, which varied by as little as 0.01% to as much as 2.5% for any individual sample.

2.3. Statistical analysis

Cluster analysis was performed on raw-scan XRD spectra using Philips X'pert High Score with default settings. Cluster analysis is an automatic four-step procedure. It consists of a comparison of each spectrum with all others and generation of a distance matrix; agglomerative hierarchical cluster analysis; determination of the number of "meaningful" clusters of the most representative member and of the furthermost members of each cluster; and Principal Components Analysis (PCA), which is an independent method of visualizing and judging the quality of the clustering. The scans are compared using a proven matching algorithm used also for qualitative phase identification. The program has been built to work specifically with diffraction patterns and is different from other software approaches, which work on the basis of image processing.

2.4. Geographic regions

In order to better describe and analyze the data, the study area was divided into four geographic regions: The North Coast, which includes all coastal samples north of Point Bonita; the South Coast, which includes coastal samples south of the Cliff House; the Golden Gate Bridge Area, which includes all samples from SF Bar and the Golden Gate west of Angel Island; and the Bay, which includes all samples in the North Bay (including San Pablo and Suisun Bays), Central Bay east of Angel Island, and South Bay (Fig. 1). These boundaries were chosen based on natural geomorphological divisions, location of major sand inputs, location of mixing zones, direction of longshore transport, and differences in mineralogy of the areas based on our statistical analyses when adjacent areas were analyzed in combination. Cluster analysis was performed on samples within the four areas (dendrograms presented) and for combinations of adjacent areas (dendrograms not presented). Cluster analyses for combined areas show that our chosen divisions are good first-order approximations of distinct source-to-sink divisions of the region, but do not further aid in understanding the sources for each region. Sediment dispersal does occur between the areas, which is discussed below.

3. Results

As expected, quartz and feldspar are the most abundant minerals found throughout the study area, with plagioclase more common than K-feldspar. The exceptions are several pyroxene- and magnetite-rich beach sands along the open coast south of the Golden Gate Bridge (Ocean Beach), which will be discussed below. Generally, pyroxene was found in 84% of sediment samples while amphibole was found in 42%. Small amounts of clay minerals were also found, which are probably components of rock fragments in the sand-sized samples. Mica was found in 52% of samples, 65% contain kaolinite, and 19% contain chlorite. Three percent or less of sand-sized samples contain additional minerals such as hematite, magnetite, ilmenite, serpentine, rutile, and epidote. Beach samples generally varied only slightly in mineralogical composition from offshore samples, containing somewhat higher amounts of quartz and pyroxene, and less feldspar, which may be due to hydraulic sorting. Beach sample mineralogy is very similar to sand-sized bedload sediment from streams and rivers. Rock samples contained a wider range of minerals, and their composition was characteristic of rock type (e.g., pyroxene-rich basalt, quartz-rich chert, feldspar-rich granitic rocks, etc.; Appendix 1).

3.1. North Coast

Pyroxene is more abundant in the Russian River sediment (6%), sandstone at Drakes Bay (11%), granitic rocks at Chimney Rock (12%), and basalt at southern Point Bonita (35%) (Fig. 1) than in the sand-sized coastal sediment from this area (mean 5%). Franciscan Complex chert (96%; Marin Headlands) and Russian River (68%) offer abundant sources for quartz, while granitic rocks at Chimney Rock (47%) and Point Reyes (61%) as well as basalt at Point Bonita (40%) are significant potential sources of feldspar for coastal sediments north of the Golden Gate (Fig. 2A). Total feldspar shows similar concentrations for the Russian River (21%) and offshore grab samples north of Point Reyes (15–19%), suggesting southern longshore transport of sand from the Russian River to the point (Fig. 3). This contrasts with prior research that pointed to a sharp decrease in heavy mineral abundance south of Bodega Head, which would eliminate the Russian River as a significant source of heavy minerals to the study region (Cherry, 1964; Minard, 1971; Demirpolat, 1991); this does not seem to apply to the light-mineral fraction. Increased concentrations of feldspar are found in granitic rocks at Point Reyes (61%) and Chimney Rock (47%), and the offshore grab sample directly adjacent to the granitic rocks has a comparable high concentration (43%). This granitic rock source is likely to provide a component to North Coast sand but it is limited in spatial extent and cannot erode fast enough to be the predominant supplier of feldspar regionally. The feldspar content (33%) of the fine-grained sandstone cliffs along Drakes Bay and a close-by offshore grab (38%) are very similar, suggesting a local source contribution from the Tertiary sandstone cropping out west of the San Andreas fault. Feldspar content then decreases slightly moving south along the coast from Drakes Estero (28–30%) but increases at Point Bolinas and Bolinas Bay (41%), Stinson Beach (33%), and Muir Beach (32%; Fig. 3), showing the influence of sandstones of the Franciscan Complex. The beach sample at Rodeo Cove and the adjacent course sandstone at Ft. Cronkite contain much less feldspar (17% and 30% respectively) than surrounding areas, suggesting a likely local Marin Headlands provenance for the beach sand. Offshore grabs just north of the mouth of the Golden Gate Bridge have feldspar concentrations similar to those of samples just south of the mouth, suggesting flow of sediment across the mouth and south along the coast, consistent with the suggestion of Schatz (1963). However, samples near the northern mouth of the Bay inlet can also be explained by mixing with sediment coming out of the Bay (Fig. 3) as can those south of the inlet. It is not possible to distinguish between these two possibilities based on mineral percentages alone. However, cluster analysis (discussed below) shows linkages of North Coast sediment with South Coast sediment supporting the suggestion of Schatz (1963).

Cluster analyses of North Coast mineralogical data associate offshore samples surrounding Pt. Reyes with offshore samples from the northern San Francisco Bar, while offshore samples in the middle of the North Coast group with the sandstone at Drakes Bay (Fig. 4). These connections suggest strong local source contributions in the central North Coast as well as longshore transport of sediment, linking the predominant sources of the North Coast. The Russian River sediment and granitic rocks at Chimney Rock and Pt. Reyes are grouped in the next tier with North Coast offshore samples, illustrating that all local sources are linked contributors. The beaches are grouped separately from the offshore samples, but within the beach cluster, middle and northern

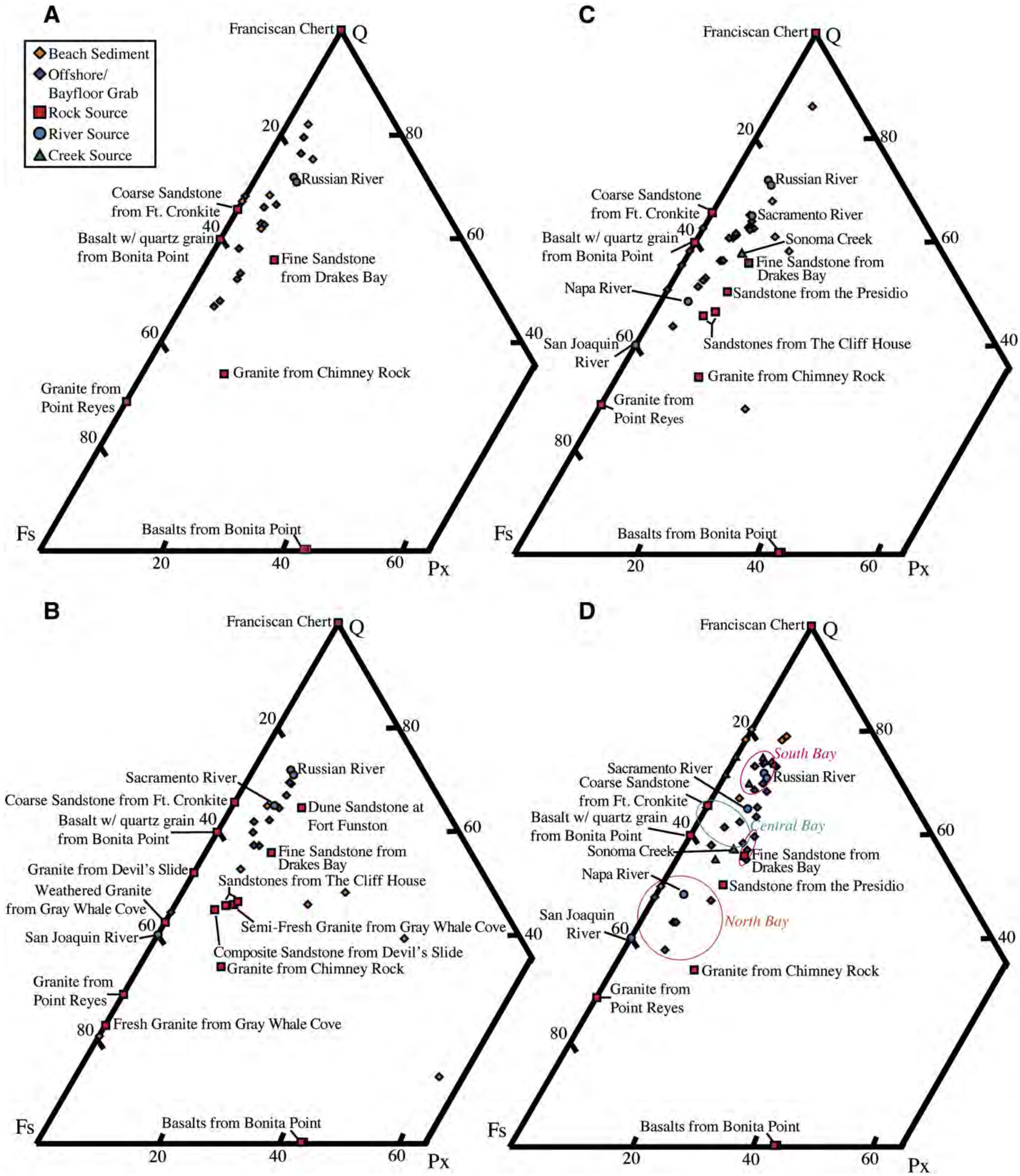

Fig. 2. Ternary plots showing relative quartz, pyroxene, and total feldspar contents of the samples analyzed in the four regions of this study: (A) North Coast, (B) South Coast, (C) Golden Gate Bridge Area, and (D) San Francisco Bay. No samples contain more than 60% pyroxene or less than 40% quartz; therefore, that sector of the plots is cut.

North Coast beaches are more closely clustered than the southern beaches, likely reflecting more varied sources and complex geology at the southern end of the North Coast. The Franciscan Complex chert (quartz) and basalt from the Marin Headlands are the least related clusters, due to their unique mineralogical signatures and small outcrop extents.

3.2. South Coast

The relatively fresh granitic rocks at Gray Whale Cove and stagnant dune sediment at Ft. Funston, as well as North Coast granitic rocks at Chimney Rock (12%) and sandstone from Drakes Bay, contain concentrations of pyroxene greater than or equal to those of the

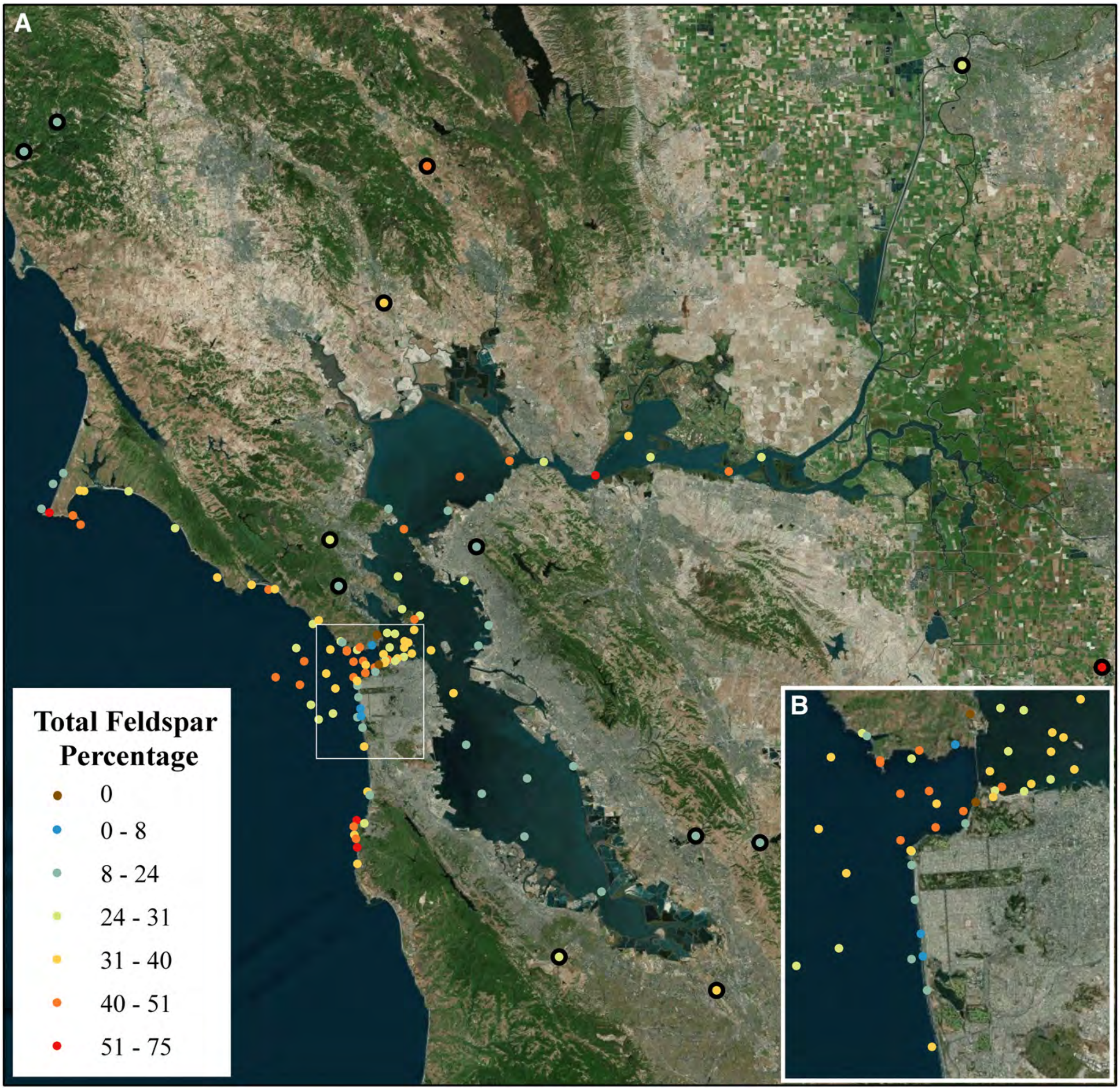

Fig. 3. (A) Map of total feldspar percentage for each sample; (B) enlargement of area outlined by white box in A.

beach and offshore sediments along the south coast. Several rock and river sources are potential significant feldspar contributors, including the granitic rocks at Gray Whale Cove (55%) and the sandstone at Devil's Slide (28%) as well as the more distant granitic rocks at Chimney Rock and Pt. Reyes, and the San Joaquin River (58%; Fig. 2B). Interestingly, beach samples at the southern end of Ocean Beach contain large amounts of magnetite (41–61%), hematite (11–27%), and for two beach samples, amphibole (14–16%). The sample from stagnant sand dunes collected south of Ocean Beach at Ft. Funston is composed of 16% magnetite and 3% amphibole but contains no hematite, suggesting a local source coupled with near-shore or beach processes of winnowing and accumulation of heavy mineral lag deposits at the southern sector of Ocean Beach and alteration of magnetite to hematite in the beach sand. Magnetite is indicative of a high-energy environment and southern Ocean Beach is a site of active coastal erosion (Barnard et al., 2007, 2012b). These heavy minerals decrease in abundance with distance from the southern end of Ocean Beach; however, even at 2.8 km to the north, magnetite is 4.2% and hematite 11%. Much of the northern San Francisco peninsula is composed of Quaternary dune sandstone and the northern and central peninsula of Late Cenozoic sandstone; both are likely sources of magnetite (e.g., Luepke, 1991), most notably the Colma Formation that composes the eroding bluffs backing the southern section of Ocean Beach and Ft. Funston (Schlocker, 1974). Granitic rocks of Montara Mountain and ultramafic rocks of the Franciscan Complex may have been the original source rocks that supplied magnetite to the much younger sandstones.

Pyroxene content is high in several beach samples along the South Coast, especially at Sharp Park Beach (40%). The nearby sandstone does not contain much pyroxene, suggesting a more distant source for the pyroxene. However, because pyroxene is susceptible to both chemical and mechanical weathering, the source is probably not too distant, most likely volcanic rocks of the Franciscan Complex that crop out at the south end of the beach and, to the north, near Mussel Rock, close to where the San

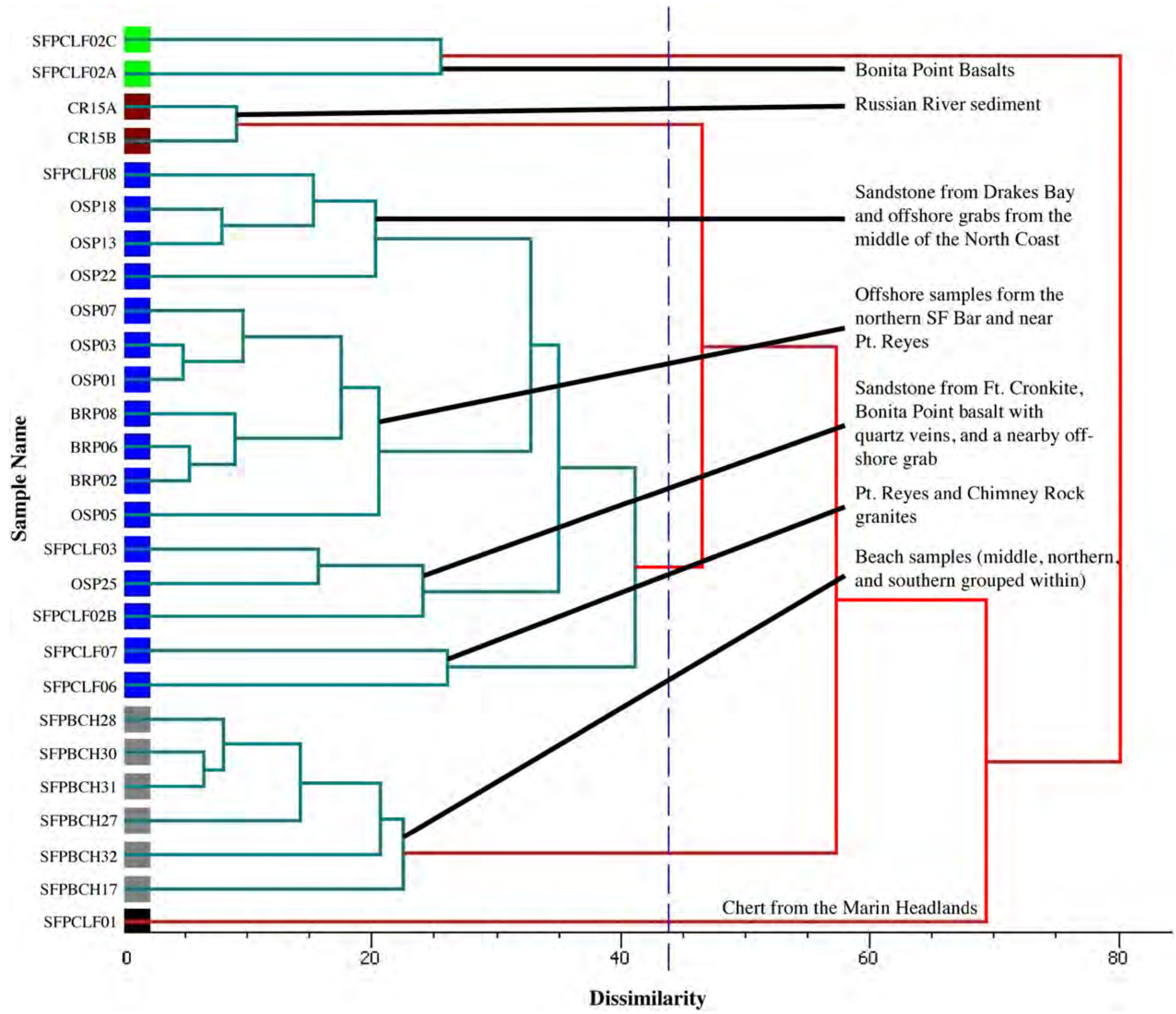

Fig. 4. Dendrogram representation of cluster analyses of XRD spectra of North Coast samples. The dashed line represents the cutoff value used to produce a meaningful set of clusters, and is based on the largest relative step in dissimilarity (between minimum and maximum cutoff values).

Andreas fault cuts across the coast (see Graymer et al., 2006). An additional source might be the Montara Mountain granitic rocks (Fig. 2B).

There is a stark contrast between the feldspar-rich southern samples near Devil's Slide, south of the littoral cell boundary (Limber, 2005), and the northern beaches and offshore grab samples, which are instead high in magnetite and/or contain larger percentages of pyroxene (Fig. 3). Offshore samples between the magnetite-rich zone (Ocean Beach) and Point San Pedro contain moderate amounts of feldspar (31–39%), appearing to link the two geographic ends.

Cluster analyses of the South Coast data closely group samples from the SF Bar with offshore samples from the northern and middle sections of the South Coast as well as the dune sandstone at Fort Funston and San Joaquin and Sacramento River sediment (Fig. 5). These samples are then grouped at the next tier with the Russian River, rocks from the North Coast, and granitic rocks from southern Gray Whale Cove, suggesting longshore transport with North Coast and SF Bay sources as well as local source contributions. The northernmost and southernmost beach sands are clustered, while the other beaches of the South Coast cluster with Franciscan Complex chert and sandstone from north of Point San Pedro, as well as the Tertiary sandstone cropping out at Point San Pedro, implying transport from other areas of the south coast. The two anomalous magnetite-rich sands cluster alone and are the least-related samples because their anomalous concentrations are likely a result of hydrodynamic forcing rather than solely source related.

3.3. Golden Gate Bridge area

The Golden Gate area samples are relatively high in feldspar, with basalt from Point Bonita having the highest feldspar content (45%) of any other nearby source rocks that supply local beaches; however, the outcrop area is rather small and this is an unlikely feldspar source for a broader area. Granitic rocks along the North Coast and the San Joaquin and Napa Rivers contain high enough feldspar to be potential major contributors to this area, but as discussed for the North Coast, the granitic rock at Point Reyes is most likely of only local significance as a source rock. The basalt at Point Bonita also contains abundant pyroxene that supplies local areas, but the sandstones from the headland north of the Cliff House, the Presidio, and Drakes Bay, and granitic rocks at Chimney Rock are the predominant potential sources of pyroxene (Fig. 2C). The beach on the south coast of the Marin Headlands adjacent to Franciscan Complex chert and the beach at Point Bonita directly below basalt outcrops both contain very similar percentages of feldspar to their adjacent cliff sources (Fig. 3). The two beach samples near Crissy Field are similar in overall mineral content to the sandstone sampled at the Presidio; however, the two beach samples contain amphibole and the sandstone does not. The Sacramento, San Joaquin, and lower Russian River samples are the only river/creek samples that contain amphibole. The fact that amphibole is absent from all rock, beach, and offshore grab samples north of the Golden Gate but found throughout the North Bay, Golden Gate, SF Bar, and northern South Bay indicates

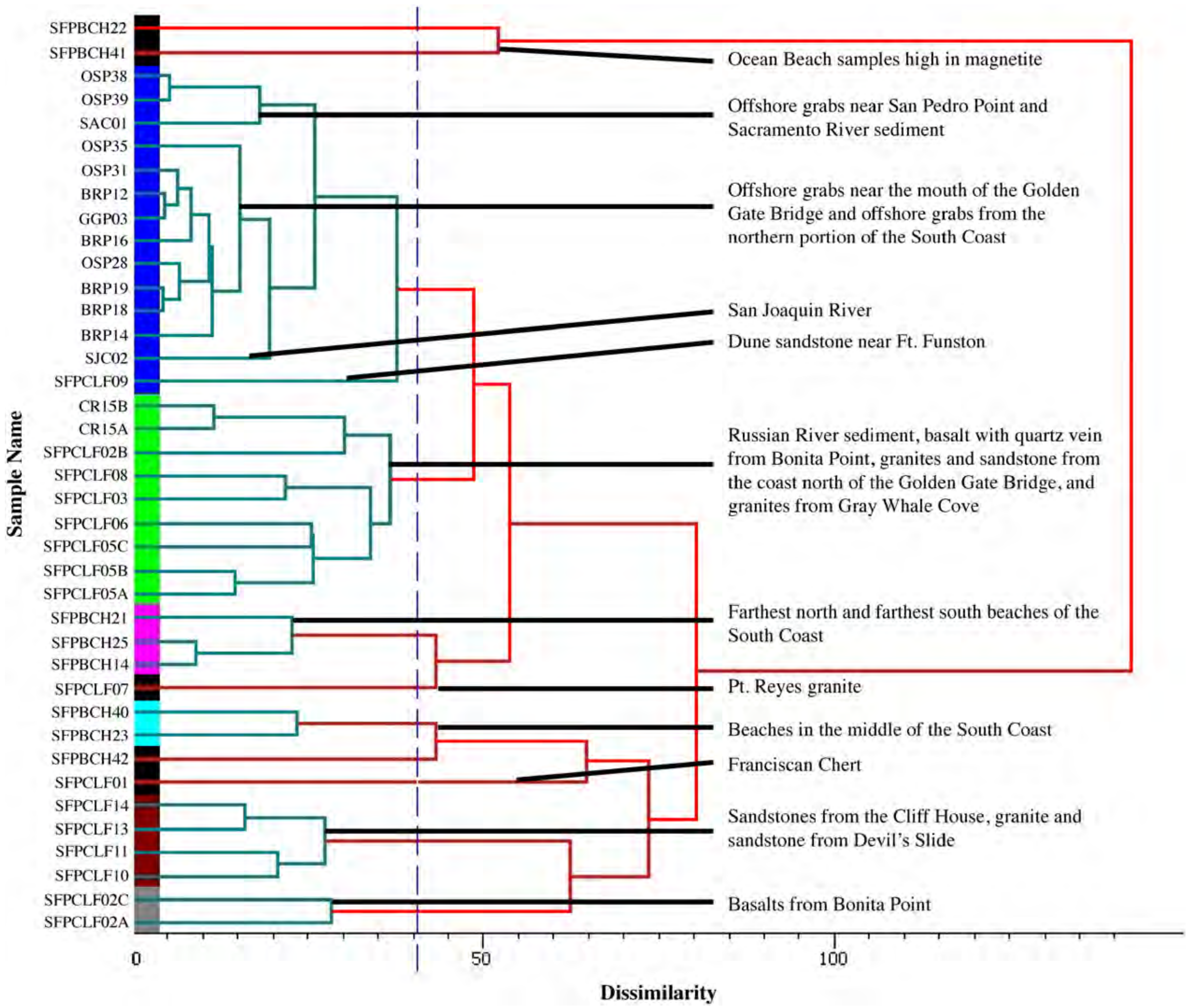

Fig. 5. Dendrogram representation of cluster analyses of XRD spectra for South Coast samples.

that sediment from the Sacramento and San Joaquin Rivers are transported through North Bay and deposited in Central Bay, including onto those beaches (Fig. 6). Baker Beach also contains amphibole as well as parts of the South Coast, such as Ocean Beach samples and the dune sandstone from Fort Funston, implying a link in sediment supply among these locations. Sediment has been suggested to move from Ocean Beach into the area of northern SF peninsula beaches (Battalio and Trivedi, 1996; Barnard et al., 2007).

Cluster analysis of data from the Golden Gate region groups offshore samples at and outside the Golden Gate Bridge with the Sacramento, San Joaquin, and Napa Rivers, which supports the transport of sediment from those rivers to seaward of the mouth of SF Bay (Fig. 7). Unlike the other three regions, the majority of beach sediments from the Golden Gate Bridge area were not placed into a cluster separate from the offshore samples, but were instead grouped with the Central Bay bayfloor samples located between the Golden Gate Bridge and Angel Island. This clustering indicates that sediment supplied to those beaches was transported through the Bay. The two beaches that are exceptions are the Marin Headlands chert- and basalt-sourced beaches described above, which did not cluster in major groups due to their reflection of local cliff source rocks.

3.4. San Francisco Bay

The sand-sized sediment within the Bay is the most diverse, including beaches with the highest quartz content (up to 79%) and bayfloor samples with more pyroxene and feldspar than the other regions. The smaller tributaries that drain into the Bay supply quartz-rich sediment, while the Napa and San Joaquin Rivers and Sonoma Creek supply abundant feldspar (Fig. 2D). Amphibole percentages show a clear relationship between the Sacramento and San Joaquin River sources and sediment in Suisun and San Pablo Bays (Fig. 6). Amphibole is present in the Sacramento River sediment (0.7%) and higher in the San Joaquin (1.2%). Suisun Bay samples contain amphibole percentages similar to the San Joaquin River that decrease slightly in content from east to west (range = 1.3–0.5%) then from north to south in San Pablo Bay, suggesting mixing and dilution of amphibole with increased distance from the Sacramento and San Joaquin river mouths. Feldspar is higher in the San Joaquin River (59%) than in the Sacramento (27%), which brackets the amounts of feldspar in Suisun Bay sediment (27–54%, mean 36%). San Pablo Bay sediment has higher average feldspar (49–51%, mean 50%) than Suisun Bay and more closely reflects feldspar contents of the Napa (46%) and San Joaquin Rivers and Sonoma Creek (34%). These trends in the North Bay demonstrate the influence of both local and more distant fluvial sources (Fig. 3). The Central Bay beaches are similar in mineralogical composition and are very high in quartz (>67%), with no discriminate mineralogical characteristics.

The South Bay bayfloor samples are also fairly uniform in mineralogical composition; however pyroxene concentrations in the southernmost South Bay samples and the eastern shoal sample are slightly higher than in the rest of the South Bay and are comparable to the pyroxene content of the eastern beach sample and the Guadalupe River sample; the Guadalupe River drains into the southernmost South Bay.

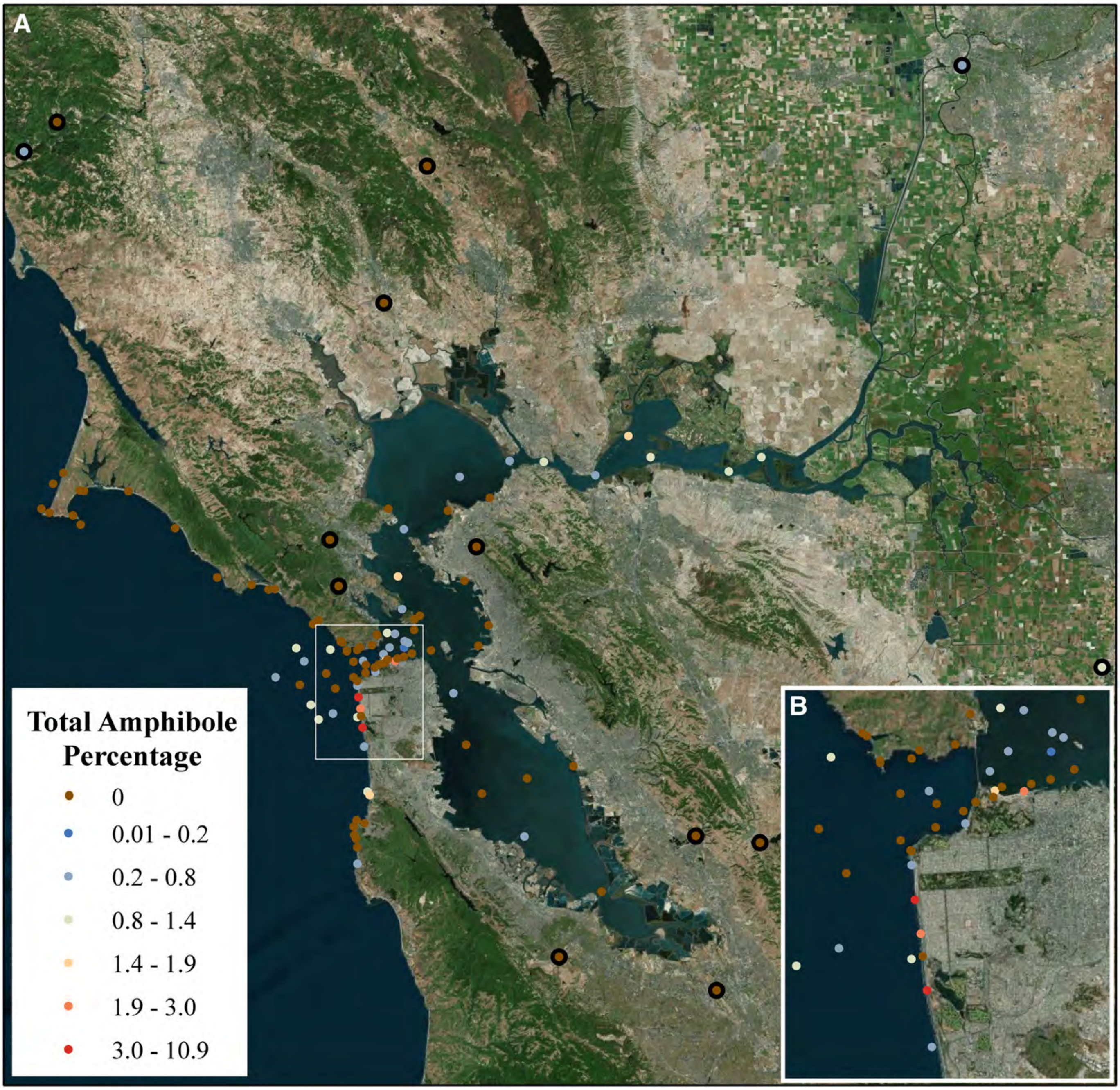

Fig. 6. (A) Map of total amphibole percentage for each sample; (B) enlargement of area outlined by white box in A.

Amphibole is found in two of the bayfloor grabs in the South Bay, but none is present in the local tributaries or beach, suggesting that sediment from the Sacramento and San Joaquin Rivers as well as possibly the South Coast can make its way to the South Bay (Fig. 6).

Cluster analysis of the SF Bay samples shows a first-tier group of the river and creek sediments with San Pablo Bay (Sacramento and Napa Rivers and local creeks) and South Bay (San Joaquin River and Sonoma and local creeks) bayfloor samples, while Suisun Bay and Central Bay grab samples form a separate first-tier group (Fig. 8). However, cluster analysis clearly shows that the influence of the Sacramento and San Joaquin Rivers can be seen throughout the SF Bay, with the most direct (unmixed) influence in South Bay, especially in the northern portion. Many other areas in SF Bay show significant mixing with sediment from local sources, for example contributions of the Napa River and Sonoma Creek to San Pablo Bay and northern South Bay sediments, and local creek contributions to southernmost South Bay sediment. There is a close connection between the Central Bay sediment and beach sands to the east, both areas reflecting relatively high-energy environments. The Central Bay is an area of extensive mixing of sediment derived from outside and inside the Bay and the main river sources show a lesser connection than for sediment elsewhere in the Bay. The East Bay beaches are supplied from this highly mixed sediment regime. An anomaly is Suisun Bay, which closely clusters with Central Bay sediment, which is difficult to reconcile because sediment from Central Bay should not travel that far to the northeast; due to hydrodynamics, sand from Central Bay is not likely to make it to Suisun Bay and the Suisun Bay signal is not found in San Pablo Bay whereas the Sacramento-San Joaquin signal is found there. However, even though there are no prominent fluvial sources to Suisun Bay other than the Sacramento and San Joaquin Rivers, there are large outcrops of Franciscan Complex rocks north of Fairfield, which may be eroded and supplied to Suisun Bay; this source would have an equivalent signature as the dominant

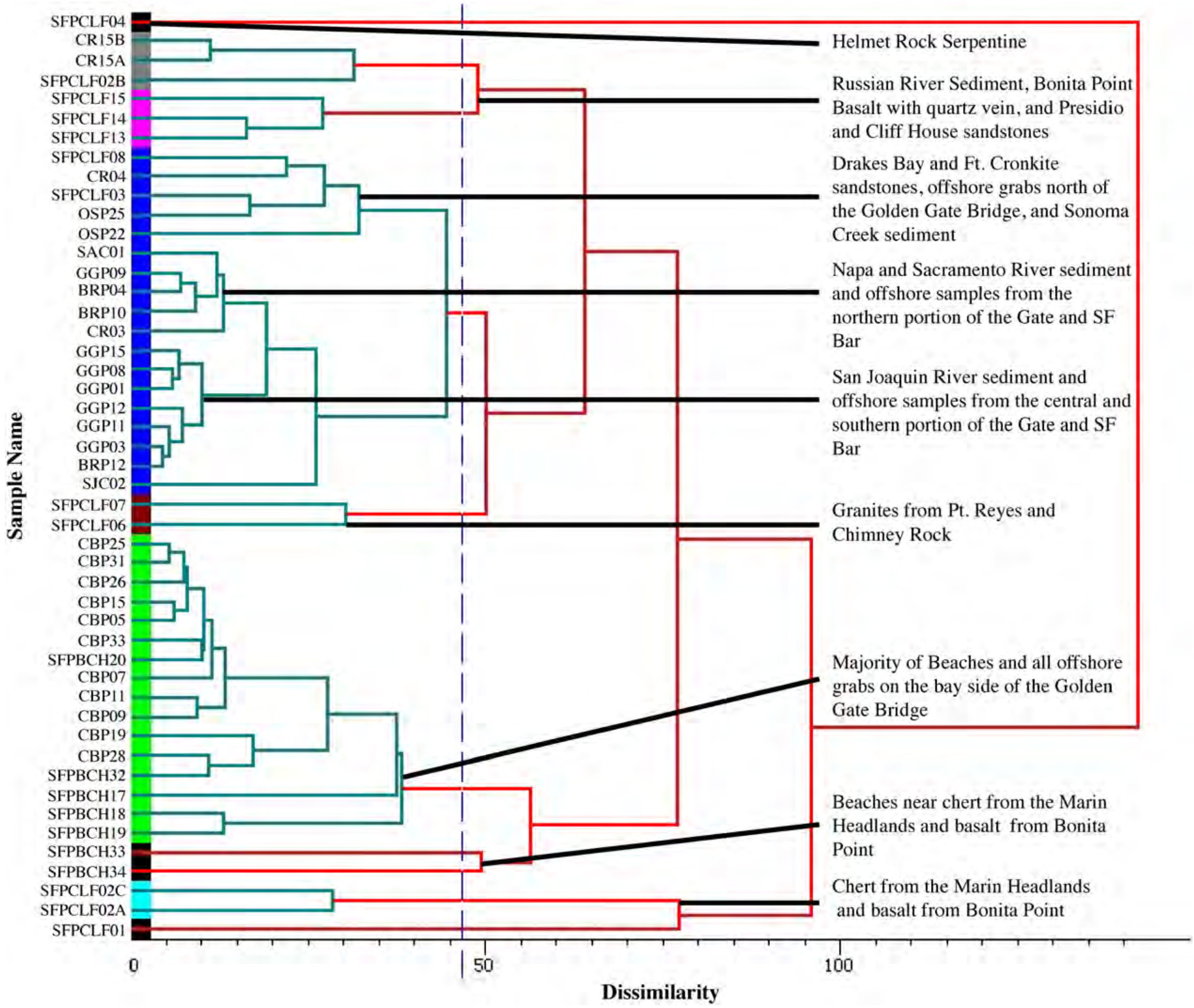

Fig. 7. Dendrogram representation of cluster analyses of XRD spectra for Golden Gate Bridge Area samples.

external-bay component for the Central Bay sediment. This conclusion is consistent with metal concentrations associated with fine-grained sediments presented by Hornberger et al. (1999). This Franciscan Complex source contrasts with the local fluvial inputs to San Pablo Bay, which erode mostly Cenozoic volcanic rocks.

4. Discussion and summary of sediment sources and transport pathways

Sediment provenance studies are commonly approached using heavy minerals, clay minerals, isotopic ratios, or chemical tracers, but rarely using XRD mineralogy of bulk sand-sized sediment because quartz and feldspar are dominant and ubiquitous and it is difficult to distinguish diagnostic types in bulk sediment derived from multiple sources. However, new pattern recognition PCA techniques that compare entire diffraction spectra offer a viable way of grouping sediment samples with their potential sources. This technique does not rely on identification and quantification of individual minerals and mineral suites, which is not straightforward for complex mixtures, and is at best semi-quantitative. Because the PCA technique looks at the entire XRD spectrum, samples with distinctly similar mineralogy patterns will always cluster together. For example, the beach sands are mature weathering products, and usually contain predominantly quartz and feldspars, so they will cluster and their scans will generally look different from those of stream and seafloor sediments and rocks. However, the PCA technique recognizes subtle similarities and differences among samples that are not of the same type, such as beach sand, granitic rocks, and seafloor sediment. The PCA approach, combined with diagnostic minerals identified by standard XRD techniques, provides a powerful tool to trace sand sources, akin to integrating isotopic and chemical tracers.

Analyses of beach, bayfloor, and offshore sand and potential fluvial and rock sources has yielded results consistent with previous work on sediment transport vectors and adds new knowledge about transport pathways and local sediment sources (Fig. 9). Along the North Coast, beach sand and offshore sands are derived predominantly from Franciscan Complex rocks delivered by local streams and the larger Russian River. Sediment from the Russian River moves south along the coast and around Point Reyes. This sediment source and transport pathways are consistent with satellite data for fine-grained sediment and coarser-grained sediment during major storms (e.g., Griggs and Hein, 1980). Outcrops of granitic rock and other coastal outcrops provide sources of sand for local beaches and near offshore sands, but are diluted with other sources from longshore transport, with the exception of parts of Drakes Bay. The general North Coast sediment signature can be traced into Central SF Bay and across the Bay mouth to the South Coast.

Most beach and offshore sands along the South Coast are derived from local outcrops and creeks, longshore transport from the North Coast, and sediment from the Sacramento and San Joaquin Rivers that transit through SF Bay, out the Golden Gate, and then along the coast to the south. Local sources or more distant sources can dominate at any particular beach along the South Coast. An additional transport pathway is north-directed longshore transport from central Ocean Beach, which rounds the point and moves into SF Bay and may contribute to north SF

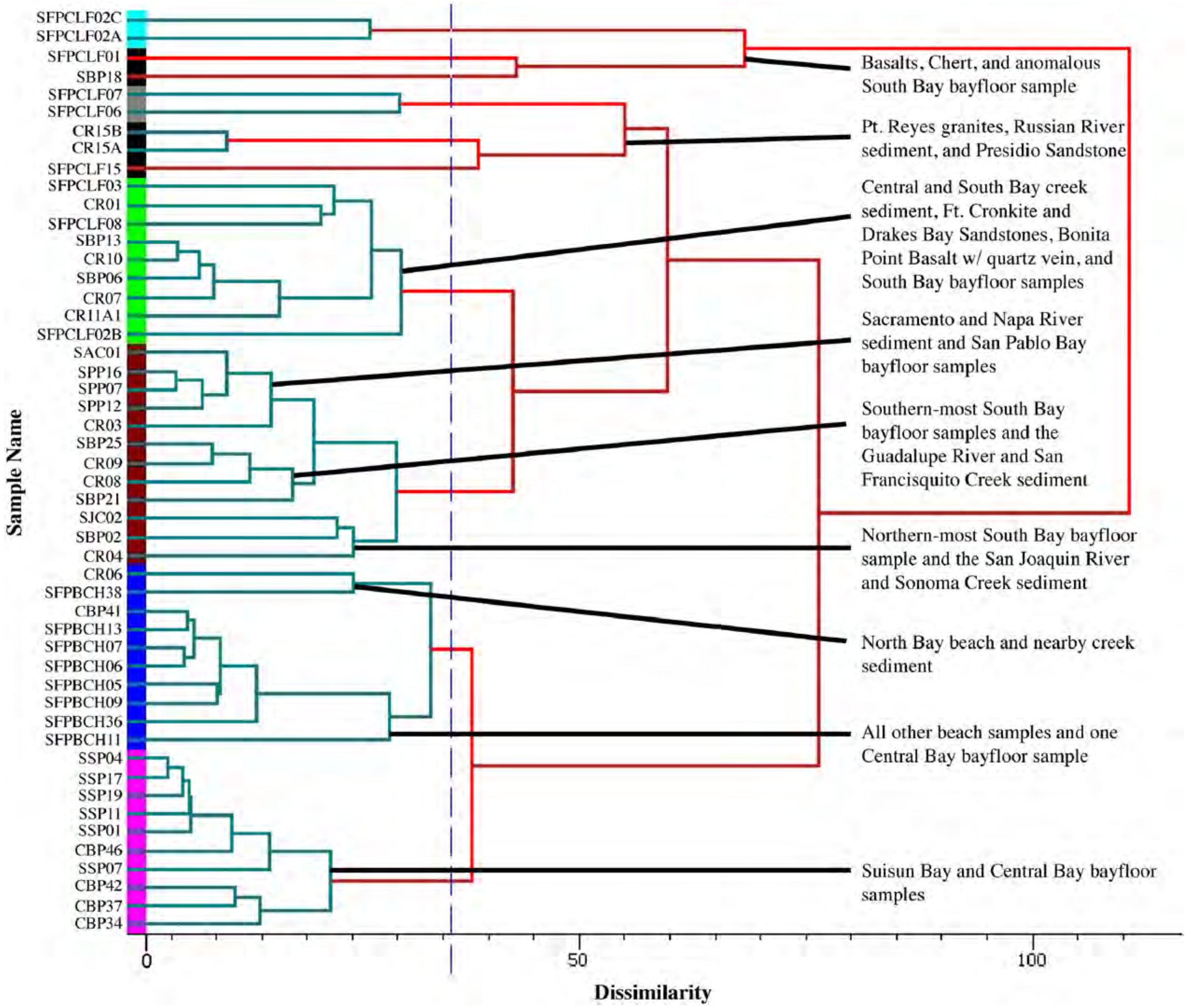

Fig. 8. Dendrogram representation of cluster analyses for XRD spectra of San Francisco Bay samples.

Peninsula beaches and offshore sediment. This process also redistributes heavy minerals that have concentrated approximately on the southern third of Ocean Beach. This transport pathway is broadly consistent with numerical model simulations that predict a net northerly transport of sediment from northern Ocean Beach and then northeastward transport around the point and into SF Bay (e.g. Barnard et al., 2007; Hansen et al., 2013-in this issue), a pathway that was originally suggested by Battalio and Trivedi (1996).

The area around the Golden Gate Bridge is a zone of mixing of sediment from various sources including longshore transport from the North Coast, westward transport from the Sacramento, San Joaquin, and Napa Rivers and Sonoma Creek, and northward transport from the area of Ocean Beach into the northern part of South Bay. Local sources are prominent for beaches along the Marin Headlands so that beaches backed by chert cliffs are dominantly chert and those backed by basalt cliffs reflect that local source. Beaches just southeast of the Golden Gate receive sand from erosion of local sandstone of the Franciscan Complex, mixed sediment of the Sacramento-San Joaquin Rivers and North Coast, and from Ocean Beach. Beaches in eastern Central Bay have the same mixed source as Central Bay sediments.

The remainder of SF Bay receives sediment predominantly from the Sacramento and San Joaquin Rivers. However, sediment from the Napa River and Sonoma Creek can be identified in San Pablo Bay and the South Bay and likely forms a small component of Central Bay sediment. The local streams flowing into the southernmost portion of South Bay are recognized in nearby bayfloor sediments. Sediment from Suisun Bay is not solely from the Sacramento and San Joaquin Rivers as might be expected, but may also receive sediment derived from erosion of the Franciscan Complex, perhaps delivered through small local creeks.

In this study, Central Bay has been identified mineralogically as a zone of mixing but also as an important source of beach-sized sediment to the ebb tidal delta at the mouth of San Francisco Bay and the outer coast region to the south. Therefore, this transport pathway revealed by the XRD cluster analysis is consistent with prior work that more qualitatively connected the removal of a minimum of 54 million m^3 of sand-sized or coarser sediment from this area since 1900 to both the widespread erosion of the ebb tidal delta and extensive erosion of the adjacent south coast shoreline (Dallas and Barnard, 2009, 2011; Barnard et al., 2012a, 2012b). With this causal link further effectively established by the data presented in this special issue (Barnard et al., 2013-in this issue-a,b; Erikson et al., 2013-in this issue; McGann et al., 2013-in this issue; Rosenbauer et al., 2013-in this issue; Wong et al., 2013-in this issue), the planning community can now more skillfully address the challenges of managing sediment in SF Bay in a manner that promotes the sustainability of open-coast beaches and submarine habitats.

Acknowledgements

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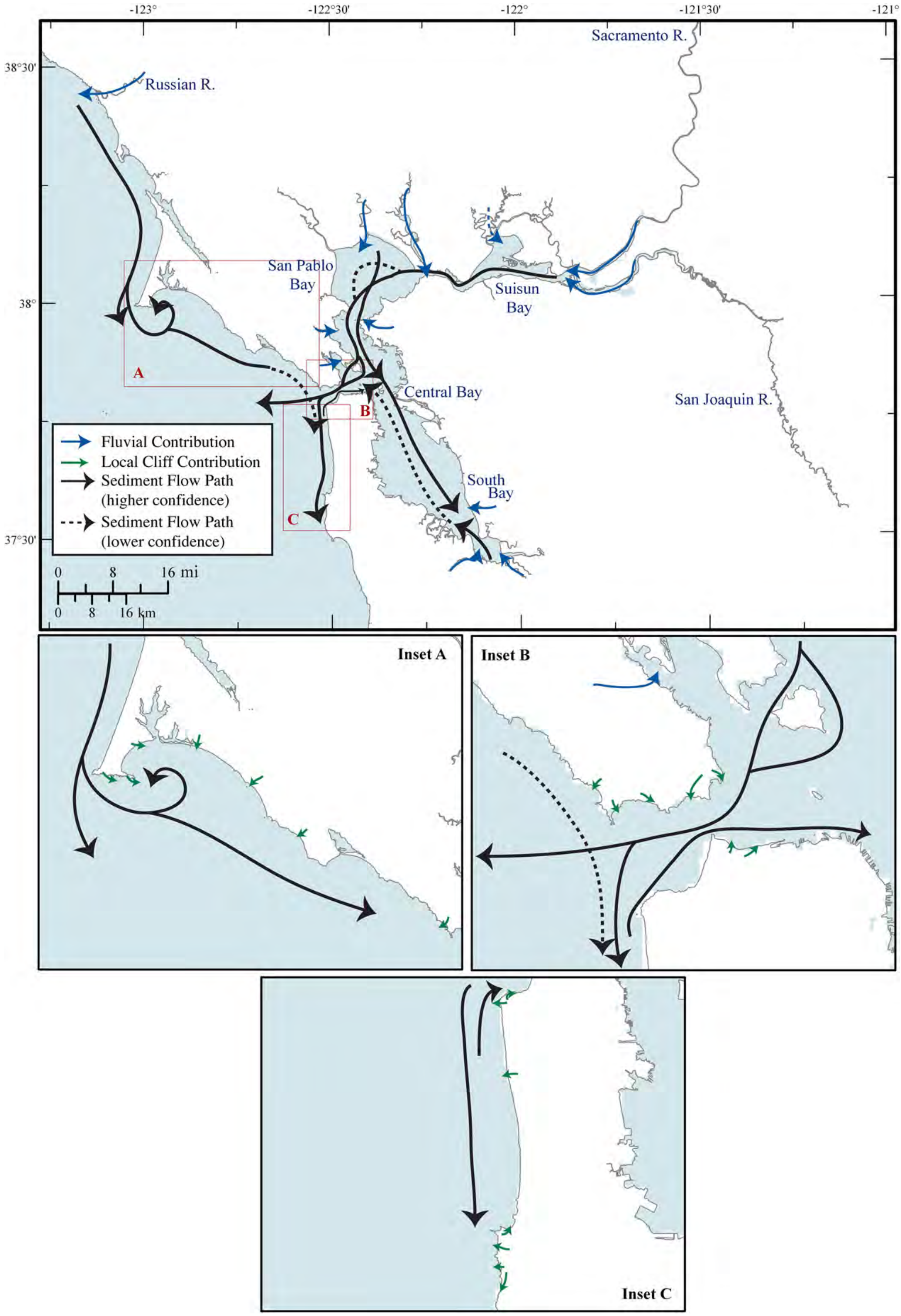

Fig. 9. Sediment provenance and inferred dispersal pathways based on XRD mineralogical and statistical data.

Appendix 1. Semi-quantitative XRD mineralogy of San Francisco Bay Coastal System samples.[a]

Sample name	BRP02	BRP04	BRP06	BRP08	BRP10	BRP12	BRP14	BRP16	BRP18
Sample type	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore
Study region	N. Coast	GGB	N. Coast	N. Coast	GGB	GGB	S. Coast	S. Coast	S. Coast
UTM_X	534142	531185	535269	538983	534658	538402	536218	539716	537323
UTM_Y	4186328	4182172	4184426	4186117	4181077	4182682	4178243	4180570	4176134
Quartz	65%	42%	46%	51%	52%	61%	64%	62%	62%
Plag	30%	20%	16%	24%	23%	18%	24%	18%	27%
Kspar	–	30%	31%	15%	18%	15%	–	15%	–
Chlorite	1.9%	–	–	1.2%	0.8%	–	1.1%	–	–
Mica/Illite	2.0%	1.3%	0.9%	0.7%	1.5%	–	1.2%	–	1.4%
Pyroxene	–	4.3%	5.3%	6.4%	5.1%	6.0%	7.7%	5.1%	7.7%
Amphibole	1.1%	0.6%	0.3%	1.4%	–	–	1.4%	–	1.1%
Kaolinite	–	–	0.9%	–	–	0.3%	–	0.3%	1.4%
Serpentine	–	1.0%	–	–	–	–	–	–	–

Sample name	BRP19	CBP05	CBP07	CBP09	CBP11	CBP15	CBP19	CBP 25	CBP26
Sample type	Offshore	Bay	Bay	Bay	Bay	Bay	Bay	Bay	Bay
Study region	S. Coast	GGB	GGB	GGB	GGB	GGB	GGB	GGB	GGB
UTM_X	539366	546581	547158	547085	547457	548199	548560	549567	549511
UTM_Y	4176977	4185446	4184692	4188466	4186400	4188361	4184839	4187301	4186378
Quartz	60%	60%	52%	60%	61%	63%	61%	55%	56%
Plag	30%	19%	14%	28%	29%	29%	36%	20%	20%
Kspar	–	14%	28%	–	–	–	–	17%	18%
Chlorite	1.3%	–	–	–	–	–	–	–	–
Mica/Illite	1.3%	–	–	1.7%	1.6%	–	1.7%	0.7%	–
Pyroxene	7.3%	5.9%	5.1%	8.2%	7.3%	7.4%	–	6.4%	6.0%
Amphibole	0.6%	0.3%	–	1.0%	0.6%	0.5%	–	0.6%	0.2%
Kaolinite	–	0.3%	0.2%	1.0%	0.6%	0.6%	1.4%	0.4%	0.3%

Sample name	CBP28	CBP31	CBP33	CBP34	CBP37	CBP41	CBP42	CBP46	CR01
Sample type	Bay	Bay	Bay	Bay	Bay	Bay	Bay	Bay	Creek
Study region	GGB	GGB	GGB	Bay	Bay	Bay	Bay	Bay	Source
UTM_X	549485	550101	550621	550927	551733	553352	549205	548645	559430
UTM_Y	4185052	4187063	4185529	4188889	4190931	4186003	4191860	4196508	4200722
Quartz	63%	56%	61%	63%	60%	61%	63%	55%	73%
Plag	28%	20%	18%	34%	30%	17%	26%	31%	20%
Kspar	–	17%	15%	–	–	17%	–	–	–
Chlorite	–	–	–	–	–	–	–	1.4%	–
Mica/Illite	1.4%	–	0.4%	2.5%	1.7%	–	1.4%	2.1%	–
Pyroxene	6.4%	6.2%	6.2%	–	6.7%	4.9%	8.2%	9.0%	7.0%
Amphibole	–	0.5%	–	–	–	–	0.5%	1.7%	–
Kaolinite	1.0%	0.2%	0.3%	1.2%	1.5%	0.2%	1.0%	–	0.7%

Sample name	CR03	CR04	CR06 A	CR07	CR08	CR09	CR10	CR11A1	CR15A
Sample type	River	Creek	Creek	Creek	Creek	Creek	Creek	Creek	River
Study region	Source	Source	Source	Source	Source	Source	Source	Source	Source
UTM_X	552798	546632	540176	538914	571580	594022	589344	600232	500086
UTM_Y	4254966	4235444	4195151	4201691	4142328	4137557	4156177	4158602	4261221
Quartz	48%	57%	72%	70%	69%	54%	72%	71%	69%
Plag	19%	34%	20%	28%	10%	22%	20%	24%	21%
Kspar	28%	–	–	–	16%	16%	–	–	–
Chlorite	–	–	–	–	–	–	–	1.9%	1.0%
Mica/Illite	1.0%	–	2.2%	1.6%	–	0.8%	1.1%	2.7%	1.8%
Pyroxene	4.5%	8.6%	4.5%	–	4.8%	6.4%	5.2%	–	6.0%
Kaolinite	0.5%	0.6%	1.2%	–	0.6%	0.6%	1.5%	–	–
Serpentine	–	–	–	0.9%	–	–	–	–	1.6%

Sample name	CR15B	GGP01	GGP03	GGP08	GGP09	GGP11	GGP12	GGP15	OSP01
Sample type	River	Bay	Bay	Bay	Bay	Bay	Bay	Bay	Near Shore
Study region	Source	GGB	GGB	GGB	GGB	GGB	GGB	GGB	N. Coast
UTM_X	495322	542311	542300	543988	542834	543676	544033	545309	499498
UTM_Y	4256994	4182145	4184367	4182762	4186051	4184496	4183893	4183541	4209650
Quartz	67%	51%	55%	50%	61%	58%	60%	52%	79%
Plag	21%	17%	17%	18%	30%	15%	18%	16%	17%

(continued on next page)

Appendix 1 (*continued*)

Sample name	CR15B	GGP01	GGP03	GGP08	GGP09	GGP11	GGP12	GGP15	OSP01
Sample type	River	Bay	Bay	Bay	Bay	Bay	Bay	Bay	Near Shore
Study region	Source	GGB	GGB	GGB	GGB	GGB	GGB	GGB	N. Coast
UTM_X	495322	542311	542300	543988	542834	543676	544033	545309	499498
UTM_Y	4256994	4182145	4184367	4182762	4186051	4184496	4183893	4183541	4209650
Kspar	–	27%	28%	31%	–	27%	16%	26%	–
Chlorite	1.3%	–	–	–	–	–	–	–	–
Mica/Illite	2.0%	–	–	0.8%	–	–	–	–	–
Pyroxene	6.8%	4.8%	–	–	7.9%	–	5.3%	5.0%	4.1%
Amphibole	0.6%	–	–	–	–	0.4%	–	–	–
Kaolinite	–	0.4%	0.5%	0.7%	1.0%	0.3%	0.3%	0.6%	–
Serpentine	1.9%	–	–	–	–	–	–	–	–

Sample name	OSP03	OSP05	OSP07	OSP13	OSP18	OSP22	OSP25	OSP28	OSP31
Sample type	Near Shore	Near Shore	Near Shore	Near Shore	Near Shore	Near Shore	Near Shore	Near Shore	Near Shore
Study region	N. Coast	N. Coast	N. Coast	N. Coast	N. Coast	N. Coast	N. Coast	S. Coast	S. Coast
UTM_X	497847	503414	503915	516858	522881	530168	536527	542840	543813
UTM_Y	4206105	4203852	4208634	4203355	4196374	4194665	4189742	4176464	4172266
Quartz	76%	45%	58%	66%	63%	52%	64%	68%	59%
Plag	19%	16%	16%	12%	12%	16%	27%	23%	18%
Kspar	–	27%	23%	18%	19%	25%	–	–	16%
Chlorite	–	–	–	–	–	–	1.3%	–	–
Mica/Illite	–	6.3%	–	–	–	–	2.1%	0.5%	0.4%
Pyroxene	5.2%	5.5%	4.0%	4.2%	5.9%	6.6%	5.8%	7.1%	5.9%
Amphibole	–	–	–	–	–	–	–	1.4%	0.6%
Kaolinite	–	0.3%	–	–	–	0.8%	–	0.6%	0.3%

Sample name	OSP35	OSP38	OSP39	SAC01	SBP02	SBP06	SBP13	SBP18	SBP21
Sample type	Near Shore	Near Shore	Near Shore	River	Bay	Bay	Bay	Bay	Bay
Study region	S. Coast	S. Coast	S. Coast	Source	Bay	Bay	Bay	Bay	Bay
UTM_X	544281	542742	542427	629018	556527	558355	560588	567022	566667
UTM_Y	4165847	4161774	4159684	4269301	4179899	4172538	4165574	4167734	4159472
Quartz	56%	43%	52%	61%	57%	71%	72%	56%	64%
Plag	19%	24%	32%	27%	16%	21%	23%	19%	24%
Kspar	15%	31%	–	–	22%	–	–	–	–
Chlorite	–	–	–	2.2%	–	1.4%	0.7%	–	–
Mica/Illite	–	0.9%	7.7%	2.5%	–	1.4%	1.4%	14%	3.6%
Pyroxene	8.2%	–	6.7%	6.6%	4.4%	5.1%	4.0%	7.0%	5.9%
Amphibole	1.0%	–	–	0.7%	0.7%	–	–	–	0.6%
Kaolinite	0.2%	–	–	–	0.2%	–	–	3.8%	–
Serpentine	–	1.0%	1.3%	–	–	–	–	–	2.4%

Sample name	SBP25	SFPBCH05	SFPBCH06	SFPBCH07	SFPBCH09	SFPBCH11	SFPBCH13	SFPBCH14	SFPBCH17
Sample type	Bay	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.
Study region	Bay	Bay	Bay	Bay	Bay	Bay	Bay	S. Coast	N. Coast
UTM_X	577628	573626	561550	560074	555713	561711	558110	542862	540697
UTM_Y	4151624	4169492	4189582	4186659	4205823	4207645	4195904	4155556	4187131
Quartz	68%	79%	74%	78%	79%	73%	67%	52%	75%
Plag	23%	15%	20%	16%	20%	19%	14%	40%	17%
Kspar	–	–	–	–	–	–	15%	–	–
Mica/Illite	1.5%	–	–	–	0.9%	–	–	–	–
Pyroxene	6.9%	6.5%	6.6%	6.1%	–	7.7%	4.6%	7.4%	7.7%
Amphibole	–	–	–	–	–	–	–	0.6%	–
Kaolinite	1.0%	–	–	–	0.3%	–	–	0.6%	0.4%

Sample name	SFPBCH18	SFPBCH19	SFPBCH20	SFPBCH21	SFPBCH22	SFPBCH23	SFPBCH25	SFPBCH27	SFPBCH28
Sample type	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.
Study region	GGB	GGB	GGB	S. Coast	S, Coast	S. Coast	S. Coast	N. Coast	N. Coast
UTM_X	548224	546824	545409	542838	543376	544602	543852	500941	510249
UTM_Y	4184488	4184518	4182947	4180960	4176600	4165352	4161351	4211202	4208618
Quartz	56%	59%	67%	68%	2.0%	38%	64%	82%	68%
Plag	25%	26%	23%	23%	2.0%	19%	29%	15%	15%
Kspar	–	–	–	–	5.7%	–	–	–	13%
Chlorite	–	0.8%	–	–	–	–	–	–	–
Pyroxene	16%	13%	8.9%	7.6%	–	40%	5.8%	3.6%	4.0%

Appendix 1 (*continued*)

Sample name	SFPBCH18	SFPBCH19	SFPBCH20	SFPBCH21	SFPBCH22	SFPBCH23	SFPBCH25	SFPBCH27	SFPBCH28
Sample type	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.
Study region	GGB	GGB	GGB	S. Coast	S, Coast	S. Coast	S. Coast	N. Coast	N. Coast
UTM_X	548224	546824	545409	542838	543376	544602	543852	500941	510249
UTM_Y	4184488	4184518	4182947	4180960	4176600	4165352	4161351	4211202	4208618
Amphibole	2.9%	1.9%	0.6%	0.5%	–	1.9%	–	–	–
Kaolinite	0.5%	–	0.4%	0.5%	–	–	0.5%	–	0.2%
Hematite	–	–	–	–	27%	–	–	–	–
Magnetite	–	–	–	–	61%	–	–	–	–
Epidote	–	–	–	–	–	0.8%	–	–	–
Rutile/Anatase	–	–	–	–	1.8%	–	–	–	–

Sample name	SFPBCH30	SFPBCH31	SFPBCH32	SFPBCH33	SFPBCH34	SFPBCH36	SFPBCH38	SFPBCH40	SFPBCH41
Sample type	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.	Beach Sed.
Study region	N. Coast	N. Coast	N. Coast	GGB	GGB	Bay	Bay	S. Coast	S. Coast
UTM_X	527783	531076	537328	543209	544921	550982	547269	543578	543275
UTM_Y	4195320	4194725	4190279	4186444	4186726	4190416	4206106	4174973	4177671
Quartz	67%	62%	62%	27%	85%	49%	76%	44%	2.8%
Plag	13%	13%	18%	20%	7.6%	20%	21%	23%	6.0%
Kspar	20%	20%	14%	26%	–	30%	–	–	–
Chlorite	–	–	–	3.9%	–	–	–	–	–
Mica/Illite	–	–	0.8%	–	–	0.9%	1.9%	–	–
Pyroxene	–	5.8%	5.2%	24%	6.5%	–	–	25%	14%
Amphibole	–	–	–	–	–	–	–	6.9%	2.4%
Kaolinite	–	–	0.8%	–	0.5%	0.3%	0.4%	0.7%	–
Hematite	–	–	–	–	–	–	–	–	23%
Magnetite	–	–	–	–	–	–	–	–	41%
Ilmenite	–	–	–	–	–	–	–	–	11%

Sample name	SFPBCH42	SFPCLF01	SFPCLF02A	SFPCLF02B	SFPCLF02C	SFPCLF03	SFPCLF04	SFPCLF05A
Sample type	Beach Sed.	Chert	Basalt	Basalt Qtz	Basalt	C.S.S.	W. Serp	F. Granite
Study region	S. Coast	Source	Source	Source	Source	Source	Source	Source
UTM_X	543006	545649	541338	541332	541332	540473	545896	542809
UTM_Y	4179301	4188184	4185958	4185859	4185859	4187272	4183971	4157921
Quartz	33%	96%	–	56%	–	58%	–	21%
Plag	24%	–	42%	38%	45%	30%	–	31%
Kspar	–	–	–	–	–	–	–	41%
Chlorite	1.3%	–	18%	2.4%	4.7%	–	–	4.3%
Mica/Illite	–	–	7.4%	4.0%	–	12%	–	–
Pyroxene	16%	–	33%	–	35%	–	–	–
Amphibole	11%	–	–	–	–	–	–	2.3%
Serpentine	–	–	–	–	–	–	34%	–
Hematite	11%	3.6%	–	–	–	–	–	–
Calcite	–	–	–	–	16%	–	–	–
Magnetite	4.2%	–	–	–	–	–	40%	–
Pyroaurite	–	–	–	–	–	–	26%	–

Sample name	SFPCLF05B	SFPCLF05C	SFPCLF06	SFPCLF07	SFPCLF08	SFPCLF09	SFPCLF10	SFPCLF11
Sample type	S–F Granite	W. Granite	Granite	W. Granite	F.S.S.	S.S.	W. Granite	S.S.
Study region	Source	Source	Source	Source	Source	Source	Source	Source
UTM_X	542809	542809	502305	498958	503306	543578	542661	542656
UTM_Y	4157921	4157921	4205143	4205557	4208695	4174973	4159154	4159172
Quartz	42%	40%	30%	24%	55%	52%	44%	40%
Plag	41%	55%	20%	32%	33%	19%	40%	28%
Kspar	–	–	27%	29%	–	–	–	15%
Chlorite	7.5%	2.0%	–	–	–	–	5.4%	1.0%
Mica/Illite	–	–	9.1%	14%	–	–	4.2%	4.2%
Pyroxene	9.0%	–	12%	–	11%	9.4%	–	6.3%
Amphibole	–	–	–	–	–	3.0%	–	–
Kaolinite	–	–	1.9%	–	0.7%	0.7%	–	–
Calcite	–	–	–	–	–	–	5.7%	5.2%
Magnetite	–	–	–	–	–	16%	–	–
Epidote	–	2.7%	–	–	–	–	–	–
Sepiolite	–	–	–	1.8%	–	–	–	–
Talc	–	–	–	–	–	–	0.8%	–

(*continued on next page*)

Appendix 1 (*continued*)

Sample name	SFPCLF13	SFPCLF14	SFPCLF15	SJC02	SPP07	SPP12	SPP16	SSP01	SSP04
Sample type	S.S.	S.S.	S.S.B.	River	Bay	Bay	Bay	Bay	Bay
Study region	Source	Source	Source	Source	Bay	Bay	Bay	Bay	Bay
UTM_X	542831	542787	546741	648956	549468	557441	564527	569425	576754
UTM_Y	4181617	4181663	4184216	4183572	4203200	4210664	4212924	4212782	4210877
Quartz	32%	33%	45%	39%	41%	41%	47%	57%	37%
Plag	30%	33%	36%	31%	19%	17%	18%	28%	19%
Kspar	–	–	–	27%	30%	31%	33%	–	35%
Chlorite	–	–	1.0%	–	0.8%	–	–	–	1.1%
Mica/Illite	5.6%	1.9%	6.7%	1.0%	2.1%	1.7%	1.2%	1.5%	1.1%
Pyroxene	7.0%	6.1%	9.2%	–	5.3%	5.7%	–	10%	6.6%
Amphibole	–	–	–	1.2%	0.7%	0.8%	0.6%	1.3%	0.5%
Kaolinite	1.8%	1.6%	–	0.4%	–	2.0%	0.5%	1.8%	–
Calcite	–	–	2.0%	–	–	–	–	–	–
Magnetite	3.8%	2.5%	–	–	–	–	–	–	–
Goethite	20%	22%	–	–	–	–	–	–	–

Sample name	SSP07	SSP11	SSP17	SSP19
Sample type	Bay	Bay	Bay	Bay
Study region	Bay	Bay	Bay	Bay
UTM_X	581473	584627	595785	600421
UTM_Y	4216486	4213459	4211426	4213460
Quartz	52%	55%	46%	61%
Plag	32%	31%	25%	27%
Kspar	–	–	17%	–
Chlorite	–	0.8%	0.7%	0.7%
Mica/Illite	2.1%	1.7%	1.6%	1.2%
Pyroxene	11%	11%	9.4%	8.9%
Amphibole	1.8%	1.1%	0.9%	1.3%
Kaolinite	1.7%	–	–	–

[a] Dashes = not detected; Beach Sed. = beach sediment; Offshore = samples west of the Golden Gate Bridge; Nearshore = offshore along the open coast; Bay = bayfloor samples within San Francisco Bay; N. Coast = North Coast; S. Coast = South Coast; GGB = Golden Gate Bridge Area; W. Serp = weathered serpentinite; S-F Granite = semi-fresh granite; W. Granite = weathered granite; F.S.S. = fine sandstone; C.S.S. = coarse sandstone; F. granite = fresh granite; Basalt Qtz = basalt with quartz vein; S.S.B. = sandstone bed.

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April 20, 2015

California Regional Water Quality Control Board,
San Francisco Bay Region
1515 Clay Street, Suite 1400
Oakland, CA 94612
Attn: Elizabeth Christian

Subject: U.S. Army Corps of Engineers, San Francisco District Maintenance Dredging Program, 2015 Through 2019

Dear Members of the Board:

On behalf of California's system of ports and harbors, thank you for the opportunity to comment on the Tentative Order your staff has prepared for your consideration and adoption.

As the Water Board finds it in the public interest to encourage beneficial reuse of suitable dredged material, please define "beneficial reuse." of dredged material. If this definition does not include placing the material back into San Francisco Bay, please provide the rationale as the Tentative Order comments on significant reduction of sediment loading from the Sacramento-San Joaquin River System.

Why not provide a 10-year Water Quality Certification as that was one of the stated purposes of Draft Environmental Assessment/Environmental Impact Report?

When did the Water Board consider, certify, and approve the final Environmental Impact Report for Federal Navigation Channels?

In order to provide clarity, please define San Francisco Bay and Central Bay as the terms are used in the Tentative Order. One of the projects is outside of the Bay, another is in San Pablo Bay and a third is in Suisun Bay.

Page 7, foot note *is this inner or outer?

Please provide a copy of the March 14, 2014 CDFW Letter referenced in the Tentative Order.

Hydraulic dredging includes hopper dredging and cutter head dredging. The Tentative Order wants to reduce hopper dredging and yet uses terms such as cutter heads, hydraulic suction hopper dredging, hopper dredging, and hydraulic dredging. Is the Tentative Order restricting all hydraulic dredging or just hopper dredging? This should be clarified as the Draft EA/EIR did discuss the distinction between hopper and cutter head dredging as it relates to entrainment.

Based on the Draft EA/EIR there is a ten to one ratio between mechanical dredging and hopper dredging in the time needed to dredge certain channels. The Tentative Order does not show that the Water Board considered any adverse impacts, such as noise, that may result to various aquatic species by these longer dredge times. Did they? We believe their consideration or lack of consideration should be discussed in the Tentative Order.

We request the Water Board positively affirm that additional sediment does not need to go into the water column as the Tentative Order does state “Less sediment in suspension and circulation within the Bay impairs the ability of shorelines, mudflats, and tidal wetlands to withstand erosion and inundation, especially as sea level rises. As we see the question, under current Sea Level Rise predictions from the State of California (up to 5.48 feet by the year 2100), is it better to put dredged material back into the Bay where it will increase sediment in suspension and possibly feed both mudflats and wetlands or place the sediment directly into wetlands that may or may not be able to function under Sea Level Rise and possibly not provide other benefits, such as limiting the loss of mudflats?

While the Draft EA/EIR discusses the impact of not receiving sufficient funds for the Corps to perform the maintenance dredging under Alternative 1 and 2. It only discussed the potential impacts to those navigation channels. The most likely scenario, based on the increased funding to Oakland and Richmond over the past several years, is that other projects within San Francisco Bay or along the Coast of California will not receive sufficient funding for adequate maintenance dredging. Please state that the Water Board has reviewed the socio economic, life safety and environmental impacts to other Corps’ projects within the San Francisco District and South Pacific Division due to the additional costs of dredging navigation channels in San Francisco Bay as a result of this Tentative Order. Specifically, dredging of small coastal communities such as: Moss Landing; Noyo and Morro Bay.

Again, thank you for the opportunity to comment as you continue to meet your obligations in a thoughtful and deliberative process.

Sincerely,

James M. Haussener
Executive Director

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Delivery Via E-Mail: echristian@waterboards.ca.gov

April 20, 2015

San Francisco Bay Regional Water Quality Control Board
1515 Clay Street, Suite 1400
Oakland, CA 94612

Attn: Ms. Elizabeth Christian

Re: Reissued Waste Discharge Requirements and Water Quality Certification for the U.S. Army Corps of Engineers, San Francisco District (Corps), Federal Navigation Channel Maintenance Dredging Program in the San Francisco Bay Area

Dear Ms. Christian:

We appreciate the opportunity to comment on Condition 6, Dredging and Disposal Operations – Overflow/Decanting for the Reissued Waste Discharge Requirements and Water Quality Certification for the U.S. Army Corps of Engineers, San Francisco District (Corps), Federal Navigation Channel Maintenance Dredging Program in the San Francisco Bay Area.

Our comments are based on actual water quality monitoring experience that R.E. Staite has obtained from years of dredging of clean and unsuitable sediments along the West Coast. Recently we were hired to remediate unsuitable sediments at two major shipyard and repair facilities in San Diego Bay known as the Environmental Restoration North and South Trust Shipyard Project. Water quality monitoring was a key requirement for both shipyards. We recognize sediment remediation is different than San Francisco Bay maintance dredging projects and that both San Diego Bay and San Francisco Bay have very different background levels of turbidity, however, the San Diego Bay monitoring plan goals are, like the RWQCB's, to ensure that excessive turbidity does not occur. We have reviewed the proposed water quality and monitoring plan requirements with Anchor QEA, the San Diego Bay Trustee's consultant currently handling the water quality monitoring for the San Diego Bay projects to aid in the review of components of a monitoring plan with appropriate contingency actions that are within the parameters of the RWQCB Water Certification. Our comments are intended to assist the RWQCB to create a decanting and monitoring program that complies with the San Francisco Basin Plan and is workable for dredging contractors to perform. Our comments also address what should and should not be contained in the required monitoring plans for dredging activities.

The comments provided over the next few pages reference the current text in the Tentative Order with R.E. Staite's suggestions provided below the original text.

2145 E. Belt Street, San Diego, California 92113 • phone: 619.233-0178 fax: 619.233.3706

Exceptions may be granted on a project-specific basis if the Corps submits an overflow monitoring plan, acceptable to the Executive Officer, at least 90 days prior to the anticipated dredging start date. The plan shall describe the process for monitoring compliance with the following receiving water limits within 500 feet of the dredge footprint (a shorter distance may apply in Richmond and Oakland Inner Harbors depending on the distance to the nearest eelgrass bed or patch):
· Turbidity ≤ 50 NTU (or up to 10 percent greater than turbidity at a background reference location sampled concurrently with the dredging location, if the background turbidity is greater than 50 NTU)
· Dissolved oxygen ≥ 5.0 mg/L (≥ 7.0 mg/L east of the Carquinez Bridge)
· 6.5 ≤ pH ≤ 8.5

Please delete “an overflow” monitoring plan and replace it with “a decanting” monitoring plan.

Regarding the limits for turbidity, a ten percent above background level is a very difficult standard to meet. The practical impact of this standard is that it is highly likely that a ten percent above background level will trigger multiple work stoppages. Our experience has shown (as well as a recent ACOE study) that dredging turbidity plumes rapidly dissipate. Our primary concern is that as presently drafted, the Tentative Order could result in routine work stoppages or significant slowdowns of dredging activities because the monitoring benchmark is just slightly above background levels.

Another factor that should be considered when setting turbidity limits includes the location of the monitoring station. Having sampling stations located too close to the dredging activities can further exacerbate a ten percent above background limit. In order to reduce “false alarms”, we recommend sampling at a distance of 600' only, which is the "point of compliance."

A factor not considered in the above condition is the effect of tug boat operations during monitoring activities. In some locations and tidal conditions, tug boats can create turbidity. If sampling occurs during or after tug boat operations, false readings may be received. Therefore, we recommend that no sampling occur during tug boat operations and that sampling also be delayed until tug associated turbidity has cleared. We request that the above tug boat operational factors are made a condition precedent to gathering turbidity data.

Please adopt the following:

- *Turbidity ≤ 50 NTU (or up to* ~~***10***~~ ***20*** *percent greater than turbidity at a background reference location sampled concurrently with the dredging location, if the background turbidity is greater than 50 NTU).*
- *Monitor sampling locations shall be located at the “point of compliance”, or at least 600’ from the dredging activities.*
- *Sampling shall not occur until any turbidity from tug activity clears.*

The concerns above also apply to dissolved oxygen (DO) monitoring levels. Again, it is highly likely that the combination of 'just above background levels' and near-by monitoring stations will trigger contingency plans that will significantly impact dredging operations. Please include a 20-percent decrease from background DO levels. The revised text would read:
Dissolved oxygen ≥ 5.0 mg/L (≥ 7.0 mg/L east of the Carquinez Bridge), ***or a 20-percent decrease from background DO levels.***

2) Describe how the effectiveness of economic barge loading, i.e. total cubic yards of material placed into a scow, vs. amount of suspended sediment released to the Bay will be evaluated with and without overflow;
Based on our most recent project data, it should be noted that 35% - 45% of a fully loaded scow (if not decanted) is comprised of bay water. The amount of water retained depends on the type of sediments at the project site and the type of bucket used for the operation. While the total number of disposal trips and trips saved could be estimated for each project based on the estimated production rate and the equipment planned for the project, it should be recognized that any reduction in total trips to a disposal site would be of benefit to the environment. It is suggested that the item #2 requirements be deleted.

Project-Specific Overflow Monitoring Plan Due Date: A minimum of 90 days prior to anticipated dredging start date. Dredging may not commence until the plan is approved in writing by Water Board staff.
This 90 day period fails to take into account the ACOE specification and bidding process. It is important that any monitoring program becomes part of the ACOE contract specifications so that the contractors can calculate its costs and the cost of potential work stoppages or slowdowns in its dredging operations. The second element that makes the 90 days impractical for the contractor is there is a very short amount of time between the time of award and the "notice to proceed." Most ACOE contracts require 10 days to start the dredging project from the notice to proceed, so there is little to no time to have a monitoring plan approved before dredging is scheduled to commence. As an alternative, we recommend that a "master monitoring plan" be produced that could be incorporated into the ACOE's bidding processes. By adopting one master monitoring plan, contractors can account for the plan's economic burdens and the additional time required to implement the plan. As a failsafe to a master monitoring plan, site specific requirements could be accounted for during the sediment suitability determination. Doing so at this period of time allows the contractor to prepare for additional or less stringent site specific monitoring obligations. In sum, it is recognized that the RWQCB does not have control over the ACOE bidding processes, however, it is requested that every effort be made to approve a monitoring plan prior to ACOE project bid dates to give contractors adequate time to include monitoring costs in their final bid pricing package.

Monitoring Plan
It is our understanding that the ACOE is in the process of preparing a decanting monitoring plan. Since this process is in its early stages of development, we request that the following be included in any follow-up monitoring plan that is adopted: Plan Requirement The monitoring plan requirement should be rescinded after two years/seasons if previous project monitoring data demonstrates little to no increases above background levels of turbidity, DO, or pH. Monitoring Frequency Sampling should be reduced to weekly sampling if no water quality exceedances are observed after 3 consecutive days of monitoring Testing Locations The only monitoring station needed is at the point of compliance; 600' from the dredging operation.

Turbidity Testing Within the Water Column

Our concern is that taking samples near the bottom of the bay (-2" from the bay bottom) will fail to provide any meaningful data. At the bottom of the bay there are many factors that can increase turbidity such as tides and currents. These natural forces will compromise the samples taken and not yield meaningful data. Therefore we recommend that any monitoring plan only include surface samples and a mid-level water column sample.

Contingencies for Exceedance

Please adopt alternatives other than dredging stoppages or slowdowns should there be background level exceedences. Alternatives to work stoppage may include re-testing or consultations and notifications to the USACE and/or RWQCB staff.

Monitoring Flow Chart

A Monitoring Flow Chart was prepared for the San Diego Bay Environmental Restoration North Trust North Shipyard Project by Anchor QEA. The flow chart is attached as an example of how a master monitoring plan could be sequenced and implemented.

We understand that a sample monitoring plan from Gray's Harbor, Washington was submitted to the RWQCB as a potential monitoring template. We have contacted the contractor who has been dredging in Gray's Harbor, Washington for the past six years to determine their monitoring requirements. (See attached letter - American Construction Company). Their experience has been to take only one sample, and has not included the extensive sampling locations of the Gray's Harbor plan we have recently reviewed.

Again, thank you for the opportunity to comment on the decanting condition that was included in the Reissued Waste Discharge Requirements and Water Quality Certification for the U.S. Army Corps of Engineers, San Francisco District (Corps), Federal Navigation Channel Maintenance Dredging Program in the San Francisco Bay Area. If you have any specific questions regarding our comments, or would like further clarification, please contact either Ralph Hicks Ralphh@REStaite.net or Kristin Joseph (Kristin.Joseph@mail.com), or contact us by phone at (619) 233-0178.

Sincerely yours,

R.E. STRAITE ENGINEERING, INC.

RACarpenter

R.A. Carpenter
President

Cc: Cynthia Fowler, USACE
Jessica Burton-Evans, USACE

Attachment A: Sample Flow Chart - San Diego Bay Environmental Restoration North Trust North Shipyard Project prepared by Anchor QEA.

Attachment A - Sample Flow Chart

San Diego Bay Environmental Restoration North Trust North Shipyard Project prepared by Anchor QEA.

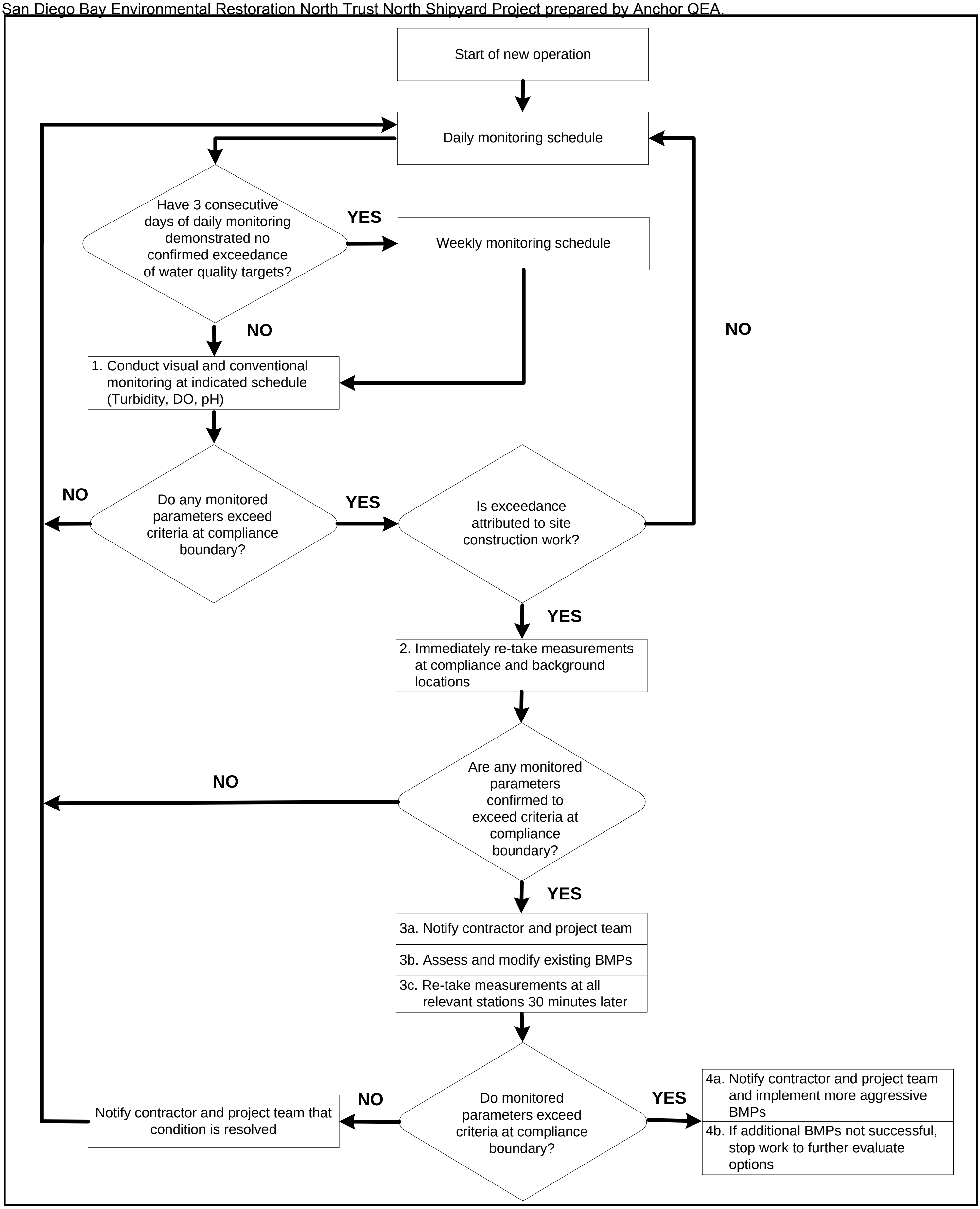

Figure 2

Water Quality Contingency Response Action Decision Flow Chart

San Diego Shipyard Sediment Site

From: Donald Snaman
To: Christian, Elizabeth@Waterboards; Christian, Elizabeth@Waterboards
Subject: RE: Notice of Public Hearing on Water Board Permit for USACE SF Bay 2015-2019 Maintenance Dredging Program
Date: Friday, March 20, 2015 6:26:38 PM

Hi Beth - I reviewed the Tentative Order and have a comment, but may be more of a correction.

Figure 7, page 36, shows the Redwood City Channel. The purple shaded disposal site is the San Leandro Marina disposal site. I believe the figrue should reference the SF-11 site typically used.

Thanks - Don

From: Christian, Elizabeth@Waterboards [mailto:Elizabeth.Christian@waterboards.ca.gov]
Sent: Friday, March 20, 2015 4:45 PM
To: Christian, Elizabeth@Waterboards
Subject: Notice of Public Hearing on Water Board Permit for USACE SF Bay 2015-2019 Maintenance Dredging Program

March 20, 2015

NOTICE OF PUBLIC HEARING

to adopt Reissued Waste Discharge Requirements
and Clean Water Act Section 401 Certification for
U.S. Army Corps of Engineers San Francisco District
2015-2019 Maintenance Dredging Program

NOTICE IS HEREBY GIVEN that the San Francisco Bay Regional Water Quality Control Board (Water Board) will consider adopting Reissued Waste Discharge Requirements and Water Quality Certification for the U.S. Army Corps of Engineers, San Francisco District (Corps) federal navigation channel maintenance dredging program in the San Francisco Bay Area, and for disposal and beneficial reuse of dredged material created by these activities for a five-year period (2015 – 2019).

The public hearing information is as follows:

DATE: May 13, 2015

TIME: 9:00 a.m. (approximate)

LOCATION: Elihu M. Harris State Building
First Floor Auditorium
1515 Clay Street
Oakland, CA 94612

STAFF CONTACT: Elizabeth Christian

San Francisco Bay Regional Water Quality Control Board
1515 Clay Street, Suite 1400
Oakland, CA
94612
510.622.2335
(ph.)
510.622.2460
(fax)
echristian@waterboards.ca.gov

MATERIALS: The proposed Tentative Orders and applications for 401 water quality certification will be available online beginning March 20, 2015, at: http://www.waterboards.ca.gov/sanfranciscobay/board_decisions/tentative_orders.shtml or http://www.waterboards.ca.gov/sanfranciscobay/public_notices/

The 30-day public comment period for the Tentative Orders will begin on March 20, 2015. Staff would appreciate submission of comments by April 15, 2015, but will accept comments submitted no later than 5:00 p.m. on April 20, 2015. All written comments on the proposed orders are due by this date to the staff contact identified above. Additionally, all evidence, testimony, and exhibits to be offered at the hearing must be submitted in writing by this date to the above staff contact. Non-evidentiary policy statements to be made at the hearing need not be submitted in advance.

Prior to the hearing, Water Board staff will post on the above website any proposed changes to the Tentative Orders, along with written responses to comments received during the public comment period. The Water Board will receive oral public testimony on the proposed amendment at the hearing.

The public hearing will be conducted in accordance with the California Code of Regulations, title 23, section 649.3. Time limits may be imposed on oral testimony at the public hearing; groups are encouraged to designate a spokesperson. All exhibits presented at the hearing, including charts, graphs, and other testimony must be left with the Water Board. They will become part of the administrative record.

A map and directions to the hearing are available online at http://www.waterboards.ca.gov/sanfranciscobay/about_us/directions.shtml. The location of the hearing is accessible to persons with disabilities. Individuals who require special accommodations are requested to contact Executive Assistant Angela Tsao, (510) 622-2399, antsao@waterboards.ca.gov, at least five (5) working days before a meeting. TTY users may contact the California Relay Service at 1-800-735-2929 or voice line at 1-800-735-2922.

Bruce H. Wolfe
Executive Officer

APPENDIX C

Response to Comments

CALIFORNIA REGIONAL WATER QUALITY CONTROL BOARD
SAN FRANCISCO BAY REGION

RESPONSE TO COMMENTS
On Tentative Order for U.S. Army Corps of Engineers, San Francisco District Maintenance Dredging Program, 2015 Through 2019

We received five comment letters during the public comment period, which closed on April 20, 2015, and we have reviewed and considered the comments contained in those letters. The comments and our responses are presented here. Staff initiated changes are presented at the end of our responses.

Comment letters received:

1. U.S. Army Corps, San Francisco District (Lt. Col. John C. Morrow)
2. San Francisco Baykeeper (George Torgun)
3. California Marine Affairs and Navigation Conference (James M. Haussener)
4. R.E. Staite Engineering, Inc. (R.A. Carpenter)
5. Port of Redwood City (Don Snaman)

Comment Letter No. 1: U.S. Army Corps (USACE)

Comments 1.1 – 1.5: Maintenance of the federal navigation channels is vital to navigational safety (i.e., reducing the risk of vessel collisions, groundings, allisions [defined as, the running of one vessel against another stationary vessel], and oil spills) and to the regional economy, which depends on navigation access to and from Bay Area ports and harbors. The Corps expressed concerns that using clamshell dredge equipment, rather than hopper dredges, may slow down dredging. "The Tentative Order is inconsistent with the Basin Plan because it fails to give the beneficial use of navigation equal weight with other beneficial uses of the Bay."

Response

We acknowledge the vital role that navigation plays in the region's economy and the necessity of dredging to ensure safe navigation. We do not agree, however, that the Tentative Order is inconsistent with the Basin Plan. The Tentative Order protects all existing beneficial uses listed in Finding 21, including navigation, consistent with maximum benefit to the people of the State. We propose a Tentative Order that preserves the USACE's ability to dredge all channels to current maintained depths, taking into account specific conditions that preclude changes in equipment type, such as the need to dredge the Main Ship Channel with a hopper dredge. Imposing conditions that modify the type of equipment used does not inhibit USACE's ability to conduct dredging. The USACE conceded in the EA/EIR that any additional time required to use clamshell versus hopper dredges would have a short-term, less-than-significant adverse impact. (Impact 3.10-1: Potential to Disrupt or Impede Marine Navigation). The resulting Tentative Order is a balanced proposal that protects navigation but also reduces environmental impacts to the maximum extent possible, as required by CEQA. (Pub. Res. Code § 21002 and *County of San Diego v. Grossmont-Cuyamaca Community College Dist.* (2006) 141 Cal.App.4th 86 [It is the policy of the State of California that "public agencies should not approve projects as proposed if there are feasible alternatives or feasible mitigation measures available which would substantially lessen the significant environmental effects of such projects…."].)

Comment 1.6: "We requested a Water Quality Certification pursuant to the federal Clean Water Act and not a Waste Discharge Requirement. A Waste Discharge Requirement is specific to the state Porter-Cologne Act and not a requirement of the federal Clean Water Act. Because there has been no clear and explicit waiver of sovereignty with respect to the Porter-Cologne Act, we do not have the authority to apply for and are not seeking a Waste Discharge Requirement. As such, in the title and throughout the document, please delete Waste Discharge Requirement (WDR) and replace with Water Quality Certification (WQC)."

Response
Pursuant to Water Code section 13263(d), the Board may prescribe waste discharge requirements (WDRs) although no discharge report has been filed. Furthermore, from 1990 to the present, the Board has regulated USACE's maintenance dredging activities under WDRs. Initially, the Board issued WDRs every 2-3 years for USACE maintenance dredging. After adoption of the Long-Term Management Strategy (LTMS) Management Plan in 2001, WDRs were issued for 3-year periods corresponding with the LTMS in-Bay disposal reduction step-down periods. USACE provides no reference to any new provision of law or change in circumstance that would restrict the Board's ability to continue to regulate USACE's maintenance dredging activities under WDRs. WDRs are appropriate where, as in this activity, there are ongoing discharges. Moreover, the Board may modify WDRs more easily than a stand-alone section 401 Water Quality Certification (WQC) to react to changed circumstances and/or new information during the term of the permit.

There is a clear and explicit waiver of sovereignty in this case. The Water Boards' authority is pursuant to the Porter-Cologne Water Quality Control Act. (Wat. Code, § 13000 *et seq*.) Porter-Cologne applies to federal agencies, "to the extent authorized by federal law." (Wat. Code, § 13050, subd. (c).) Under the Supremacy Clause (U.S. Const., art. VI, cl. 2.), and the doctrine of sovereign immunity, federal agencies and facilities are subject to state law only to the extent authorized by Congress. (*Hancock v. Train* (1976) 426 U.S. 167.) Any such authorization must be "clear and unambiguous" and any waiver must be narrowly construed. (*Goodyear Atomic Corp. v. Miller* (1986) 486 U.S. 174, 180.) Because only Congress may waive sovereign immunity, any such waiver will be found within a federal statute.

There are two waivers of sovereign immunity within the federal Clean Water Act (CWA) (33 U.S.C. § 1251 *et seq*.): CWA § 313 and CWA § 404(t). Both sections contain similar language; however, the former is a more general sovereign immunity waiver applicable to "the discharge or runoff of pollutants," while the latter is more specific and applies to the "discharge of dredge or fill material in any portion of the navigable waters." Both sections require federal agencies to comply with both substantive and procedural requirements set forth by the applicable state. Both the U.S. Supreme Court and the Ninth Circuit Court of Appeals have upheld requirements of state and local governments to obtain permits pursuant to the Clean Water Act waivers of sovereign immunity. (*See Cal. Coastal Com. v. Granite Rock Co.* (1987) 480 U.S. 572; *Friends of the Earth v. U.S. Navy* (9th Cir., 1988) 841 F.2d 927.) However, any such WDRs issued would be limited to Clean Water Act requirements.

WDRs in this case are consistent with the waiver of sovereign immunity; WDRs are limited to federal Clean Water Act requirements but, as stated above, have the added advantage of providing the Board with flexibility to modify them under statutory re-opener provisions.

Comment 1.7: "The Water Quality Certification should only apply to the discharge of dredge material and not the dredging action."

Response

We disagree. USACE's own website states "Corps permits are also necessary *for any work, including construction and dredging*, in the Nation's navigable waters." (USACE website, "Obtain a Permit" [emphasis added].) In the Frequently Asked Questions section of the website, the Corps advises that "Any person, firm, or agency (including Federal … agencies) planning to *work in navigable waters* of the United States *or* discharge… must first obtain a permit from the Corps of Engineers." (*Id*.) Moreover, U.S. EPA and USACE have consistently required permits of any person who undertakes dredging activities that involve more than incidental fallback. In 2001, USACE and U.S. EPA issued a final rule, known as "Tulloch II," which included the following provision:

> The Corps and EPA *regard* the use of mechanized earth-moving equipment to conduct landclearing, ditching, channelization, in-stream mining or other earth-moving activity in waters of the United States as resulting in a discharge of dredged material *unless project-specific evidence shows that the activity results in only incidental fallback*.

(66 Fed.Reg. at 4575 [codified at 33 C.F.R. § 323.2(d)(2)(i) and 40 C.F.R. § 232.2(2)(i)] [emphasis added]). In short, it is USACE's standard operating procedure to require a permit for any dredging activity. It should also be noted that there are, in fact, actual discharges associated with most dredging operations (i.e., resuspension of sediment due to clamshell bucket disturbance of the bottom and overflow from hydraulic hopper dredges).

The need for a federal permit (as required by USACE and U.S. EPA) triggers the need for WQC under CWA section 401.[1] Only the *potential* for a discharge is necessary to trigger a WQC; an actual discharge or a "discharge of a pollutant" is not required. The language of CWA section 401(a)(1) is written very broadly with respect to the activities it covers: "Any applicant for a federal license or permit to conduct *any* activity including, but not limited to, the construction or operation of facilities, which *may* result in *any discharge* into the navigable waters, shall provide the licensing or permitting agency a certification from the State in which the discharge originates." (Emphasis added.)

Consequently, the discharge need not be a certainty, only that it "may" occur. In addition, the Water Board has authority to regulate dredging-related impacts to beneficial uses such as preservation of rare and endangered species and fish migration, which are water quality standards under the federal Clean Water Act.

Comment 1.8: "The Water Board only has jurisdiction on the placement of material dredged from the Main Ship Channel at the Ocean Beach Demonstration Site and not SF-8.

Response

A portion of the SF-8 site is within the 3-mile limit (i.e., is within both State waters and Clean Water Act section 404 permitting jurisdiction). This area is approximately 3,200 feet long by approximately 400 feet wide at its narrowest (northern) end and approximately 1,100 feet wide at its widest (southern) end (see map below).

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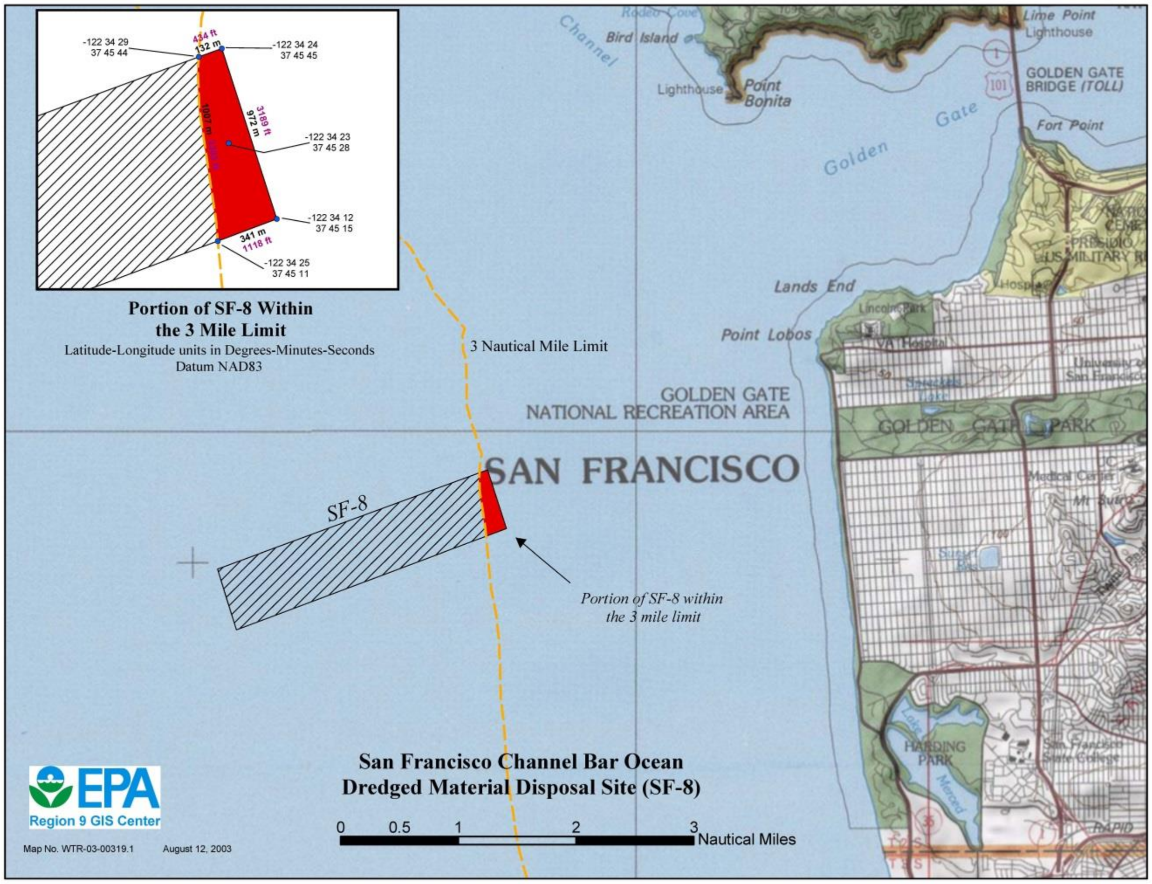
[1] USACE has, on numerous times in the permitting process, conceded that it must obtain WQC for its dredging activities and further committed to not proceed with maintenance dredging without WQC. This is consistent with USACE's own regulations. (33 C.F.R. § 336.1, subd. (a)(2) [USACE practice is to seek WQC for its dredging projects, even though USACE does not issue itself a permit for dredging].)



Comment 1.9: "With regard to suspended sediment in the Bay, the statement on page 2, item 6 states: " ...in the mid-2000s, scientists from the U.S. Geological Survey identified a significant reduction in suspended sediment loading from the ... river system. Less sediment in suspension and circulation within the Bay impairs the ability of shorelines, mudflats, and tidal wetlands to withstand erosion and inundation, especially as sea level rises." There are likely other environmentally sensitive and feasible possibilities for keeping sediment in the Bay through strategic placement.

Response

We agree that strategic in-Bay placement of dredged material where it can be demonstrated to deposit on/nourish tidal marsh or mudflat habitat provides environmental benefit and should be further studied.

Comment 1.10: "On page 3, item 7, please delete " ... calculated as 0. 7 mcy times five years." Under the Long Term Management Strategy's Management Plan, allocations are only to be established if dredged material in-bay disposal volume limitations are exceeded. Because in-bay disposal limits have not been exceeded, it is not appropriate to unilaterally impose allocations in this Tentative Order."

Response
The text that USACE requests we delete was included as background information to show how we calculated the 5-year maximum in-Bay disposal limit of 3.5 mcy, which is based on an average annual in-Bay disposal volume of 0.7 mcy. There is no annual limit or "allocation" on in-Bay disposal in the Tentative Order. Provision 1 on page 20 states "This Order authorizes... Dredging up to 12.4 mcy of sediment...with disposal of a maximum of 3.5 mcy at the in-Bay disposal sites." We see no need to delete the text in Finding 7.

Comment 1.11: "Table 1 (project summary table) was amended to constrain hopper dredge use per the reduced hopper dredge alternative. Please revise Table 1 per the project specifically requested in our Water Quality Certification application."

Response
Public Resources Code section 21002 declares the policy of the State that "agencies should not approve projects as proposed if there are feasible alternatives or feasible mitigation measures available which would substantially lessen the significant environmental effects of such projects." Table 1 was intentionally revised to reflect the project that the Water Board is approving, which eliminates or substantially lessens all significant effects on the environment where feasible but still authorizes USACE to conduct all maintenance dredging described in the application.

Comment 1.12: "Page 10, item 16, please clarify paragraph 2 to read: ' ... the Corps must consult with the appropriate *federal* resource agency.'"

Response
The text in the Tentative Order has been revised per the comment.

Comment 1.13: "Pages 10 and 11, item 16, please clarify paragraph 3 to include: 'There is no explicit waiver of federal sovereignty requiring federal agencies to comply with state listed special status species laws, including threatened or endangered species laws.'"

Response
The second sentence at the top of page 11 says: "As a federal agency, USACE is not required to obtain authorization from CDFW for incidental take of State-listed species because there has been no waiver of federal sovereignty with respect to the California Endangered Species Act (CESA)." The text proposed by USACE is redundant; therefore, we do not see a reason to add it.

Comment 1.14: "Please change 'formal endangered species consultation' to 'formal federal Endangered Species Act consultation' or 'federal ESA.'"

Response
The text in the Tentative Order has been revised per the comment.

Comment 1.15: "Please delete the last paragraph starting with 'This Order requires that the Corps comply with the programmatic LTMS work windows ... ' We do not agree that the Water Board has the authority to enforce the federal ESA under section 401 of the Clean Water Act. Further, as a federal agency, the USACE is not required to comply with the California

Endangered Species Act or consult with the California Department of Fish and Wildlife (CDFW).”

Response

By requiring compliance with the LTMS work windows, the Water Board is not attempting to enforce the federal ESA. The intent is to ensure that project activities do not adversely impact preservation of rare and endangered species (RARE), a beneficial use of San Francisco Bay and its tributaries as set forth in the federally-approved Basin Plan. The RARE beneficial use, which is a water quality standard as defined by the federal Clean Water Act, includes protection of both federal and State-listed species. The U.S. Supreme Court has determined that a state’s 401 water quality certification can place prerequisites on a license that the discharge will not violate certain water quality standards, “*including those set by the State's own laws*.” (*S.D. Warren v. Maine Board of Environmental Protection* (2006) 547 U.S. 370, 374; Water Quality Improvement Act of 1970, § 103, 84 Stat. 108 [emphasis added].)

In addition, although USACE is not required to comply with CESA or consult with CDFW, the Water Board must comply with CESA when issuing WDRs and WQC. Under CESA, “all state agencies ‘*shall* seek to conserve endangered species and threatened species and *shall* utilize their authority in furtherance of the purposes of’ CESA.” (*Kern County Water Agency v. Watershed Enforcers* (2010) 185 Cal.App.4th 969, 980 [citing Fish & G. Code § 2055] [emphases added].) The reduced hopper dredging alternatives comply with CESA because they substantially lessen significant effects of maintenance dredging on two State-listed species, the delta and longfin smelt.

We do not currently have evidence on which to base a determination that the reduced hopper dredging alternatives are not feasible. We do, however, have an opinion from CDFW that “*the Project, as proposed, would substantially reduce the number of an endangered, rare, or threatened species*. In addition, the combined cumulative impact associated with this Project and the effects of other projects causing related impacts would be significant.” (March 14, 2014, memorandum from CDFW to Bruce Wolfe.)

We acknowledge that CEQA and CESA do not apply to USACE independently of the 401 context. To the extent that the Board must comply with CEQA and CESA in preparing a 401 WQC, however, those laws remain relevant. Moreover, to the extent that the Board adopts conditions as part of a 401 WQC to ensure compliance with applicable water quality standards and other appropriate requirements, those conditions become part of the permit. (CWA § 401(d).) Section 401 (d) states that:

> “Any certification provided under this section *shall* set forth any effluent limitations *and other limitations*, and monitoring requirements necessary to assure that any applicant for a Federal license or permit *will comply with any applicable effluent limitations and other limitations*, under section 1311 or 1312 of this title, standard of performance under section 1316 of this title, or prohibition, effluent standard, or pretreatment standard under section 1317 of this title, *and with any other appropriate requirement of State law* set forth in such certification, and shall become a condition on any Federal license or permit subject to the provisions of this section.”

The Basin Plan designates Preservation of Rare and Endangered Species and Migration as beneficial uses, which are applicable water quality standards as defined by the federal Clean Water Act.

Finally, Title 23 of the California Code of Regulations, section 3859 states that "Conditions *shall* be added to any certification, if necessary, to ensure that all activities will comply with applicable water quality standards and other appropriate requirements."

For these reasons, conditions protecting federal- and State-listed species are necessary and appropriate.

Comment 1.16: "Pages 11 and 12, item 17: the discussion of the entrainment risk assessment is not accurate. As indicated by the United States Fish and Wildlife Service (USFWS) and USACE's Engineer, Research, and Development Center (ERDC), the estimates of entrainment are likely very high. Please update the Tentative Order discussion to include information presented in the draft EA/EIR (December 2014) and in the USFWS's 2014 Biological Opinion for maintenance dredging of Suisun Bay Channels.

Response
We did not revise the Tentative Order in response to this comment. The entrainment risk discussion in Finding 17 is based on the information presented in the December 2014 draft EA/EIR and acknowledged the uncertainty in the entrainment estimates:

> "…Many factors are associated with the accuracy of these projections. The small sample size of entrained fish (18 longfin smelt and 4 delta smelt), combined with the low percentage of dredged material sampled result in a high degree of uncertainty as to the accuracy of the entrainment estimates."

Comment 1.17: "Page 13, item 18: there is no evidence that the proposed project would substantially lessen the number of an endangered, rare, or threatened species. Further, as discussed in the draft EA/EIR, ERDC's entrainment risk assessment, and the 2014 Suisun Bay Biological Assessment, the entrainment study likely overstates the entrainment risk. Finally, the Tentative Order does not take into account the minimization measures to reduce entrainment risk or and the mitigation measure to compensate for potential entrainment. Please revise this statement accordingly, taking into account the opinions of the experts and the minimization and mitigation measures."

Response
Finding 18 explains the Water Board's obligation to comply with CESA when issuing WDRs and WQC to USACE, which necessitated consultation with CDFW regarding entrainment impacts to special status fish species. CDFW provided a memorandum dated March 14, 2014, stating that USACE's proposed project would substantially reduce the number of an endangered, rare, or threatened species (i.e., longfin smelt and delta smelt). To reduce impacts to a less-than-significant level, CDFW recommended reducing hopper dredging to a minimum in San Francisco Bay and implementing the avoidance, minimization, and mitigation measures required by the Tentative Order. Inclusion of the minimization measures and mitigation in the USACE Proposed Project does not fully implement the avoidance measures – reduced hopper dredging - recommended by CDFW. The Water Board, in its consultation with CDFW, considered the opinions and minimization and mitigation measures referenced in the comment. We have revised the Tentative Order to include the CDFW March 14, 2014 memorandum as an attachment.

Comment 1.18: "Page 13, item 18: the discussion of Fish & Game Code section 2053: ' ... the policy of the State that State agencies should not approve projects ... which would jeopardize the

continued existence of any endangered species ...if there are reasonable and prudent alternatives available consistent with conserving the species.' No analysis was conducted by the CDFW or the Water Board asserting that the proposed project would result in jeopardy to any listed species. Please delete this statement as no jeopardy analysis was conducted."

Response

As stated in response to the previous comment, CDFW determined that USACE's proposed project would substantially reduce the number of an endangered, rare, or threatened species (i.e., longfin smelt and delta smelt). In addition, CDFW determined that the combined cumulative impact associated with the project and the effects of other projects causing related impacts would be significant. The reference to State policy related to conserving endangered species under Fish and Game Code section 2053 is relevant.

Comment 1.19: "Page 13: the avoidance and minimization measures proposed would reduce the risk of entrainment to less-than-significant under the proposed action. Therefore, a reduced hopper dredge alternative is not warranted."

Response

The avoidance and minimization measures proposed *in conjunction with reduced hopper dredging* would reduce the risk of entrainment to less-than-significant. Please refer to response to Comments 1.1-1.5 and 1.17, concerning the requirements CEQA and CESA impose on the Board.

Comment 1.20: USACE considers a Tentative Order requiring a reduced hopper dredge alternative to exceed both the federal standard and the State's authority under section 401 of the Clean Water Act. USACE maintains that, per 33 C.F.R. § 337.2, if the State imposes conditions which exceed those needed to meet the federal standard or when an agency requires special conditions or implementation of an alternative which the federal standard does not, such as reducing the use of hopper dredges in San Francisco Bay, dredging would be deferred until the issue is resolved. Deferred dredging, even temporarily, could result in adverse effects to the economy of the region and the State and, therefore, is not "feasible" as defined under CEQA (i.e., capable of being accomplished in a successful manner within a reasonable period of time, taking into account economic, environmental, social, and technological factors).

Response

There are three issues here: 1) whether the reduced hopper dredging alternatives are "feasible;" 2) whether reduced hopper dredging exceeds the federal standard and the State's authority under section 401 of the CWA; and 3) whether deferred dredging will result in adverse effects on the State and regional economy.

<u>Feasibility</u>

We know that the reduced hopper dredging alternatives are feasible. Mechanical clamshell dredges have been used in the past and are planned for the future due to the lack of availability of hopper dredges and other reasons. In fact, due to the expected government hopper dredges being unavailable due to maintenance/repair work and dredging scheduled in other USACE districts, all in-Bay dredging in 2015, and possibly 2016, are likely to be performed via contractor-provided clamshell dredges.

Therefore, we do not currently have evidence on which to base a determination that the reduced hopper dredging alternatives are not feasible.

The only impediment presented to date regarding the feasibility of reduced-hopper dredging alternatives is the contention that such an alternative is not within USACE's current budget. "When economics is used as a factor to support a finding of infeasibility, the agency must support the finding with specific data that shows the additional cost or lost profits are great enough to make it impractical to proceed with the project. The fact that an alternative may be more expensive than the project does not necessarily make it infeasible." (Bass, et al., CEQA Deskbook (3d ed., 2012).) Even the fact that an alternative would require an act of Congress (in this case a budget increase) is not sufficient to establish infeasibility. (*Save Round Valley Alliance v. County of Inyo* (2007) 157 Cal.App.4th 1437, 1464-65.)

The Council on Environmental Quality Guidelines are consistent:

> 2b. Must the EIS analyze alternatives outside the jurisdiction or capability of the agency or beyond what Congress has authorized?
>
> A. An alternative that is outside the legal jurisdiction of the lead agency must still be analyzed in the EIS if it is reasonable. A potential conflict with local or federal law does not necessarily render an alternative unreasonable, although such conflicts must be considered. Section 1506.2(d). Alternatives that are outside the scope of what Congress has approved or funded must still be evaluated in the EIS if they are reasonable, because *the EIS may serve as the basis for modifying the Congressional approval or funding in light of NEPA's goals and policies*.

(See Forty Most Asked Questions Concerning CEQ's NEPA Regulations, 23 March 1981; 46 Fed. Reg. 18026 (1981) [citing section 1500.1(a)].)

The Federal Standard and the Board's Authority Pursuant to CWA §401.
The Board's authority under CWA section 401 is described above in response to comment 1.15. In short, CWA section 401 requires that the Board certify that the project is in compliance with water quality standards or otherwise condition the project to ensure such compliance. The conditions of the Tentative Order are intended to protect the beneficial uses of Rare and Endangered Species and Migration, which are included in the applicable water quality standards. It is clear from the legislative history of the 1977 amendments to the Clean Water Act that Congress intended that the Corps alter operations to abide by water quality standards, even if it required additional funds:

> "The amendment to section 404 clarifies the intent of Congress relative to the dredging activities of the U.S. Army Corps of Engineers. To maintain navigation on the Nation's waterways is in the national interest. However, **corps dredging activities**, like any municipal or industrial discharge to the Nation's waters, or any private dredging activities, **should be conducted in compliance with applicable State water quality standards. The corps, like other Federal agencies, should be bound by the same requirements as any other discharger into public waters.**"

***

> **"Pursuant to this amendment, the corps may be required by the States in some instances to <u>expend additional funds</u> to protect water quality. The committee supports funds for this purpose. It is the responsibility of the Secretary of the Army to seek such funds from the Congress, with the support of the Environmental Protection Agency."**

(Committee on Environment and Public Works, S. REP. 95-370, 69, 1977 U.S.C.C.A.N. 4326, 4394.)

Case law on CWA section 404(t) reiterates that "The legislative history indicates that Congress' intent in enacting the 1977 amendments was to subject the Corps' *channel-dredging* activities to state water-quality standards promulgated pursuant to the CWA, while preserving its authority to maintain navigation." (*In re Operation of the Missouri River System Litigation* (8th Cir. 2005) 418 F.3d 915, n.4 [emphasis in original].)

Congress and the Courts have repeatedly advised that "the Endangered Species Act and the Clean Water Act 'should be read together, so that compliance with one statute does not come at the expense of the other.'" (*National Wildlife Federation v. United States Army Corps of Engineers* (D. Or. 2001) 132 F.Supp.2d 876, 891.) And, in fact, there are a number of examples where USACE has altered operations and spent millions of dollars on studies to formulate alternatives to meet water quality standards. (*Id.* at 886 [multi-year, multi-million dollar study to formulate alternatives for protection of aquatic resources].)

An even more recent case evaluated an argument, not unlike that of USACE, concerning economic feasibility and involving operations of the Central Valley Project (CVP) and the effects of pumping on the delta smelt. (*San Luis & Delta-Mendota Water Authority v. Jewell* (9th Cir. 2014) 747 F.3d 581.) The Ninth Circuit evaluated whether the mission of the Central Valley Improvement Act (an Act with similar language to the USACE regulations) took precedence over the Endangered Species Act. The court recognized the critical nature of the CVP (not unlike the critical nature of navigation dredging conducted by USACE) but ultimately noted that Congress had already struck the balance and made "a conscious decision … to give endangered species priority over the 'primary missions' of federal agencies." (*Id.* at pp. 636-37.)

> As the Supreme Court observed in Tennessee Valley Authority v. Hill: **"It may seem curious to some that the survival of a relatively small number of three-inch fish ... would require the permanent halting of a virtually completed dam," but "the explicit provisions of the Endangered Species Act require precisely that result."** 437 U.S. 153, 172–73, 98 S.Ct. 2279, 57 L.Ed.2d 117 (1978). Such species have been "afforded the highest of priorities," by Congress, even if it means "the sacrifice of the anticipated benefits of the project and of many millions of dollars in public funds." Id. at 174, 98 S.Ct. 2279 (footnote omitted). **The law prohibits us from making "such fine utilitarian calculations" to balance the smelt's interests against the interests of the citizens of California.** Id. at 187, 98 S.Ct. 2279. **Consequently, any other "[r]esolution of these fundamental policy questions"** about the allocation of water resources in California **"lies ... with Congress** and the agencies to which Congress has delegated authority, as well as with state legislatures and, ultimately, the populace as a whole." Baltimore Gas & Elec., 462 U.S. at 97, 103 S.Ct. 2246.

(*Id.* at p. 593.) We currently have no evidence in the record to suggest that it is not possible to obtain funding from Congress. (*Flanders Found. v. City of Carmel-by-the-Sea* (2012) 202 Cal.App.4th 603, 620-21 ["Before a legislative body may approve a project with a significant environmental impact, it is 'required to make findings identifying … the '[s]pecific … considerations' that 'make infeasible' the environmental superior alternatives….'"].) Rather, USACE has stated, with no legal analysis or reference to any document, that the reduced dredging alternatives do not meet the federal standard and, in the face of numerous cases to the contrary, that it does not have the authority to ask Congress for additional funding to fund the increased costs of those alternatives.

USACE states, with no supporting facts or legal references, that the reduced hopper dredging alternatives in the Tentative Order exceed the federal standard. The federal standard is defined as the least-costly dredged material disposal alternative or alternatives consistent with sound engineering practices, *and* meeting the environmental standards established by the section 404(b)(1) evaluation process or ocean dumping criteria (33 C.F.R. § 335.7, emphasis added). The 404(b)(1) evaluation process clearly supports the use of measures, such as reduced hopper dredging, which will reduce adverse effects on the aquatic ecosystem. Here are just a few excerpts in that vein:

- "Fundamental to these Guidelines is the precept that dredged or fill material should not be discharged into the aquatic ecosystem, unless it can be demonstrated that such a discharge will not have an unacceptable adverse impact either individually or in combination with known and/or probably impacts of other activities affecting the ecosystems of concern." (40 C.F.R. § 230.1.)
- "[N]o discharge of dredged or fill material shall be permitted if there is a practicable alternative to the proposed discharge which would have less adverse effect on the aquatic ecosystem…." (40 C.F.R. § 230.10 (a).)
- "An alternative is practicable if it is available and capable of being done after taking into consideration cost, existing technology, and logistics in light of overall project purposes." (40 C.F.R. § 230.10 (a)(2).)
- "[N]o discharge of dredged or fill material shall be permitted which will cause or contribute to significant degradation of the waters of the United States… [E]ffects contributing to significant degradation considered individually or collectively, include: (a) Significantly adverse effects of the discharge . . . including but not limited to effects on … fish." (40 C.F.R. § 230.10 (c)(1).)
- "[N]o discharge shall be permitted unless appropriate and practicable steps have been taken which will minimize potential adverse impacts of the discharge on the aquatic ecosystem." (40 C.F.R. § 230.10 (d).)
- The permitting authority (the Corps) shall determine in writing the potential short-term or long-term effects of a proposed discharge, including determinations regarding the nature and degree of effect that the proposed discharge will have on the aquatic ecosystem and organisms (40 C.F.R. § 230.11 (e)) and cumulative impacts and effects (40 C.F.R. § 230.10 (g)).
- The discharge must be specified as failing to comply with the requirements of these Guidelines where: (1) there is a practicable alternative to the proposed discharge that would have less adverse effect on the aquatic ecosystem; (2) the discharge will result in significant degradation of the aquatic ecosystem (including significant adverse effects on fish); or (3) the proposed discharge does not include all appropriate and practicable measures to minimize potential harm to the aquatic ecosystem. (40 C.F.R. § 230.12 (a).)

In making factual determinations and findings of compliance or non-compliance, the following impacts must be considered:

- The major potential impacts on threatened or endangered species from the discharge of dredged or fill material include … directly killings species. (40 C.F.R. § 230.30 (b).)

Based upon these many authorities, USACE must adopt practicable alternatives, such as altering the type of equipment used, to protect the aquatic ecosystem.

Deferred Dredging

USACE writes that, "It is USACE's primary mission to maintain safe navigation of its channels in the Bay." In negotiations with staff, USACE staff stated that maintaining the channels of the Bay is a Congressional mandate, which USACE *must* carry out. If true, then any discussion of deferred dredging is moot; USACE may not defer dredging if Congress has required it.

USACE refers to Title 33 of the Code of Federal Regulations, part 337.2. Under 337.2, the following steps would need to occur:

1) USACE would need to determine the conditions exceed the federal standard;
2) USACE would need to provide information addressing why its own project is environmentally acceptable;
3) The district engineer would need to accommodate the state's concerns to the extent practicable, and only if the district engineer determines that the state's conditions cannot reasonably be accommodated; then
4) The state will be made aware that the project has become economically unjustified.

Although the above analysis demonstrates that the Tentative Order requirements meet the federal standard, USACE asserts in its comment letter that the project does not (Step1). In conversations with USACE staff during the drafting of the EA/EIR, they stated that the USACE proposed project was environmentally acceptable because the U.S. Fish & Wildlife Service had authorized the same or similar projects in the past (Step 2).

Steps 3 and 4 have not yet occurred. Assuming those both come to pass, Title 33 of the Code of Federal Regulations, part 337.8, would be triggered, which requires that a report be made to "higher echelons." Reports may be necessary when the state issues "the certification with conditions or controls not related to maintenance or enforcement of state water quality standards or significantly exceeding the Federal standard." (33 C.F.R. § 337.8, subd. (a)(4).) As discussed above, the Tentative Order seeks to enforce water quality standards; the discussion above demonstrates that the Tentative Order meets the federal standard. To the extent USACE disagrees, the next step is for the district engineer to prepare a report "requiring action by higher authority." That report must provide the following information:

(1) Justification showing the economic need for dredging.
(2) The impact on states outside the project area if the project is not dredged.
(3) The estimated cost of agency requirements, which exceed those necessary in establishment of the federal standard.
(4) The relative urgency of dredging based on threat to national security, life, or property.
(5) Any other facts which will aid in determining whether to further defer the dredging and seek Congressional appropriations for the added expense or the need to exercise the authority of the Secretary of the Army to maintain navigation as provided by sections 511(a) and 404(t) of the CWA if the disagreement concerns water quality certification or other state permits.

In short, the required report is exactly the type of action the Tentative Order is designed to effectuate; a request to the appropriate entities to provide sufficient funding to allow USACE to continue maintenance dredging in San Francisco Bay channels using clamshell equipment. In designing the reduced hopper dredging alternatives in the EA/EIR, Board staff used a timeframe provided by USACE staff that would allow sufficient time to process a budget augmentation request. The only reason a deferral in dredging would occur is if USACE does not process the budget request in a timely fashion. For these reasons, both the Board and USACE staff agreed upon the conclusions in the EA/EIR that, "it is unknown whether … dredging could be deferred, the impacts of deferred dredging would be speculative and variable."

Comment 1.21: "The USACE disagrees with the statement '[t]here is no information in the record to date that indicates either Alternative 1 or Alternative 2 is infeasible.' As discussed above, the USACE is not authorized to execute its maintenance dredging mission in a manner which is inconsistent with the federal standard. The federal standard makes the reduced hopper dredge alternatives infeasible."

Response
Please refer to response to Comment 1.20

Comment 1.22: "To the extent that the following statement is premised to the reduced hopper dredge alternatives and fails to fully account for economic considerations, we disagree with the statement on page 17: 'The Water Board has considered and balanced the economic, legal, social, technological, and other benefits of this Order. The Water Board finds that the unavoidable adverse impacts are acceptable due to overriding concerns.' As discussed above, navigation in the San Francisco Bay Area is vital to the regional and state economy. The potential to defer dredging could have significant adverse impacts on the regional and state economy."

Response
Please refer to responses to Comments 1.1-1.5 and 1.20, which demonstrate the balance of beneficial uses we considered as well as the considerations of economic feasibility. The Tentative Order ensures sufficient time for USACE to make the requisite budget requests, and USACE has conceded that the possibility of deferring dredging is only speculative, as are the potential impacts of any deferred dredging.

Comment 1.23: "We agree with the Water Boards finding: '[m]aintaining the federal channels to their regulatory depths is critical to the region's maritime trade and the regional and national economies.' However, we are concerned that a reduced hopper dredge alternative would significantly increase the time it takes to remove shoals from the channel. Further, the potential for deferred dredging, even temporarily, could result in adverse effects to the regional and state economies."

Response
Please refer to response to Comment 1.22. In addition, USACE conceded in the EA/EIR that any additional time required to use clamshell versus hopper dredges would have a short-term, less-than-significant adverse impact. (Impact 3.10-1: Potential to Disrupt or Impede Marine Navigation)

Comment 1.24: "Page 21, item 6: please clarify that the overflow restriction is waived for both mechanical and hopper dredging if the fine-grained content is less than 20 percent

(i.e., the sediment is greater than 80 percent sand).”

Response

The text of Provision 6 has been revised per the comment as follows:

> “Overflow/Decanting *During Mechanical Dredging*: No water entrained during dredging (aka overflow or decant water) shall be discharged from any vessel containing dredged material characterized as containing greater than 20 percent fines (silt- and clay-size particles), with the exception of spillage incidental to clamshell bucket operations. *Decanting is allowed when the fine-grain content of the dredged material is less than 20% (i.e., the sediment is greater than 80 percent sand).*

Provision 7 applies specifically to overflow during hopper dredging and already states that there is no overflow restriction if the dredged material is greater than 80 percent sand.

Comment 1.25: “Page 21, item 6, please clarify the statement: "2) describe how the effectiveness of economic barge loading, i.e. total cubic yards of material placed into a scow, vs. amount of suspended sediment released to the Bay will be evaluated with and without overflow."

Response

The component of the monitoring plan required in Provision 6 and referenced in the comment was intended to compare the increase in suspended sediment in the water column during overflow vs. non-overflow conditions. This can be incorporated into the first component of the monitoring plan, so the text quoted above has been revised to read:

> “In addition, the monitoring plan shall: 1) describe how the temporal and spatial extent of the suspended sediment plume associated with overflow/decant discharge will be characterized *and compared to non-overflow conditions*; 2) describe reporting format and frequency; and 3) include a contingency plan in the event of an observed exceedance of one or more water quality objectives caused by overflow/decant discharges.”

Comment 1.26: “It is not clear what the Water Board's expectation is if we do not receive additional Congressional appropriations to implement the phased-in reduction of hydraulic suction hopper dredging inside San Francisco Bay. Further, pursuant to the federal standard, the USACE does not have authority to request additional funds above the federal standard.”

Response

Please see response to Comment 1.20 regarding the federal standard. We expect that USACE will either comply with the Tentative Order as written, and request additional funding as necessary, or propose an alternative equally protective of the preservation of rare and endangered species and fish migration beneficial uses and request that the Water Board reopen and revise the WDRs/WQC. The only alternatives presented in the FEIR for which significant impacts were reduced to less than significant involved a reduction in hopper dredge use combined with other avoidance, minimization, and mitigation measures.

Comment 1.27a: “The phased-in hopper dredge reduction alternative presupposes that the Water Board has section 401 jurisdictions over dredging operations, as opposed to only the discharge of dredged material.... Because under the USACE regulations implementing section

404 discharges into waters of the United States, there is no substantive requirement for the USACE (or any other entity) to obtain a permit to conduct dredging activities, the Water Board has no jurisdiction over the methods by which the USACE accomplishes its dredging...Therefore, there is no requirement to obtain a section 401 Water Quality Certification for the dredging activity.

Response

Please refer to response to Comment 1.7. In particular, USACE has, on numerous times in the permitting process, conceded that it must obtain a WQC for its dredging activities and further committed to not proceed with maintenance dredging without a WQC. This is consistent with USACE's own regulations. "Corps regulations indicate that the Corps will seek 401 certification for Corps' dredging projects … even though the Corps is not issuing itself a permit." (U.S. EPA, *Clean Water Act Section 401 Water Quality Certification: A Water Quality Protection Tool for States and Tribes* (2010), citing 33 C.F.R. § 336.1, subd. (a)(2).)

Comment 1.27b: "…the goals of the Clean Water Act are accomplished by the regulation or elimination of the discharge of pollutants. The regulatory scheme does not include within its provisions, regulations pertaining to the possible entrainment of fish. To the extent that Congress intends for this to be regulated, it is accomplished under the provisions of the federal Endangered Species Act. Accordingly it is the opinion of the USACE that under the Basin Plan, the Water Board is without authority to establish conditions, which purport to limit the dredging methods chosen by the USACE.

Response

We disagree that we do not have authority to address the possible entrainment of fish. Please refer to the discussion in response to comment 1.15. Water quality standards do not apply only to pollutant discharges but also include designated (beneficial) uses. "States and tribes may include limitations or conditions in their certifications as necessary to ensure compliance with water quality standards and other provisions of the CWA and appropriate requirements of state or tribal law. **Conditions to protect water quality need not focus solely on the potential discharge.**" (EPA 401 Handbook p. 27, citing 33 USC 1341(d); CWA §401(d) *S. D. Warren Co. v. Maine Board of Environmental Protection et al*, 547 U.S. 370, 126 S.Ct. 1843 (2006); and *Jefferson County PUD v. Washington Dept. of Ecology,* 511 U.S. 700, 711 (1994).)

The Basin Plan includes beneficial uses for fish migration and preservation of rare and endangered species that are water quality standards. The Board is entitled to attach conditions to a WQC that protect these beneficial uses.

The water quality objective relating to population and community ecology is an additional potential basis for requiring conditions in a WQC that will protect endangered species. The population and community ecology water quality objective states:

> The health and life history characteristics of aquatic organisms in waters affected by controllable water quality factors shall not differ significantly from those for the same waters in areas unaffected by controllable water quality factors.

Moreover, the antidegradation policy supports adoption of conditions in a WQC that protect beneficial uses. (State Board Reso. No. 68-16.)

Please also refer to response to Comment 1.20, citing to numerous 404(b)(1) guidelines that instruct USACE to protect species including a requirement to consider:

> The major potential impacts on threatened or endangered species from the discharge of dredged or fill material include … directly killings species. (40 C.F.R. § 230.30 (b).)

Comment 1.28: "Please delete item 13, "Entrainment Monitoring for Implementation of Reduced Hopper Dredging Option l0a" on page 25. For reasons discussed above in item 26, the Water Board has no authority to require entrainment monitoring of hopper dredges."

Response
We are not deleting Provision 13. Entrainment monitoring is necessary to determine whether avoidance/minimization measures are successful and to further refine measures to protect beneficial uses impacted by entrainment. Monitoring is authorized under section 401, subdivision (d) of the Clean Water Act:

> Any certification provided under this section shall set forth any effluent limitations and other limitations, and monitoring requirements necessary to assure that any applicant for a Federal license or permit will comply with any applicable effluent limitations and other limitations….

Please also refer to the response to Comment 1.27b.

Comment 1.29: "Page 27, please delete: ' ... and with other applicable requirements of State law' or clarify which state laws are being complied with. As a federal agency, the USACE may only comply with those state laws for which Congress has waived Federal sovereignty."

Response
We have not revised the Tentative Order. The language USACE requests we delete is taken directly from Clean Water Act section 401, subdivision (d):

> Any certification provided under this section shall set forth … limitations … necessary to assure that any applicant … will comply with any *applicable* effluent limitations and other limitations, … *other appropriate requirement of State law*….

Comment 1.30: "Page 28, item 27: please delete reference to the Porter-Cologne Water Quality Control Act. As a federal agency, the USACE does not comply with the state Porter Cologne Act."

Response
Please refer to response to Comment 1.6.

Comment 1.31: "This may be boiler plate language; however, if work accomplished under the rescinded order is challenged by a third party, what is the impact of the rescission?

Response
The 2007 Order is rescinded and is no longer in effect. It is unclear what third party challenge USACE contemplates.

Comment Letter No. 2: San Francisco Baykeeper (Baykeeper)

Comment 2.I. "The Application and TO Fail to Evaluate Numerous Impacts Related to Sediment Transport and Depletion… the TO fails to consider current scientific evidence showing a direct connection between the loss of sediment from the Bay ecosystem caused by dredging and other related activities and outer coast erosion…"

Response
We disagree that there is a direct connection between outer coast erosion and dredging. Sediment dredged from most of the federal navigation channels is typically characterized as the marine clay-silt deposit termed "Bay Mud"—the exceptions being the San Francisco Main Ship Channel (MSC) in the San Francisco Bar, Suisun Bay Channel and New York Slough, and the portions of Pinole Shoal Channel, that have historically been greater than 80 percent sand.

Dredged material that USACE could potentially be allowed to take out of the Bay/ebb tidal delta system to the deep ocean disposal site SF-DODS, 55 miles east of the Golden Gate, is typically Bay Mud, which would not deposit on outer coast beaches under natural conditions, even if it were left in the system. Contrary to Baykeeper's contention, the USACE dredged material most likely to impact coastal erosion – sand - stays within the Bay/ebb tidal delta system.

Outer coast erosion, such as the extreme erosion observed at southern Ocean Beach, is driven by the loss of sand-sized sediment from the San Francisco Bay/coastal sediment transport system. USACE is engaged in efforts to replenish the loss of sand due to outer coast erosion. USACE currently places sand dredged from the MSC at the Ocean Beach Demonstration Site (OBDS), in waters of the Pacific Ocean adjacent to the south-of-Sloat-Boulevard stretch of Ocean Beach. The OBDS is located where waves can potentially feed sediment toward the southern reach of Ocean Beach to help mitigate ongoing shoreline erosion in the area.

Sand dredged from the Suisun Channel is placed is typically placed at the SF-16 placement site adjacent to the northern side of the channel and material from Pinole Shoal, which has a highly varied sand content, ranging from 10 to 98 percent, is typically placed at the SF-10 placement site in southern San Pablo Bay. Dredging in these locations puts material directly back into the Bay/ebb tidal delta system.

Comment 2.I.A: The Application and TO improperly rely on the Policy Environmental Impact Statement/Programmatic Environmental Impact Report (EIS/EIR) completed in October 1998; it is unclear whether the Regional Board has reviewed the current literature on sediment transport/deficit in San Francisco Bay.

Response
Most of the studies cited by Baykeeper are concerned with the loss of fine- to coarse-grained sand, ebb-tidal delta erosion, and open coast beach erosion, rather than the Bay Mud typically dredged from the navigation channels. We do not expect USACE's dredging program to have a significant impact on *outer coast* beach erosion as explained in the response to Comment 2.I.

We do, however, share Baykeeper's concerns about the overall sediment deficit *inside* the Bay. While the Tentative Order implements the LTMS 2001 Management Plan, which relies on the findings of the

LTMS EIS/EIR from 1998, it does consider the current scientific evidence regarding sediment deficit. Finding 6 of the Tentative Order acknowledges the overall reduction of suspended sediment loading to the Bay, which is discussed in the studies cited by Baykeeper, and the need to maximize beneficial reuse of dredged material for habitat restoration along the Bay margin:

> "As the science and knowledge regarding climate change and the resulting increase in sea level rise has grown, it is now recognized that the low-lying areas of the Bay, which were once historical marshes, are in jeopardy of being inundated both by increasing sea level and through storm surges that are occurring more frequently and at greater intensity than previously experienced. In addition, in the mid-2000s, scientists from the U.S. Geological Survey identified a significant reduction in suspended sediment loading from the Sacramento-San Joaquin river system. Less sediment in suspension and circulation within the Bay impairs the ability of shorelines, mudflats, and tidal wetlands to withstand erosion and inundation, especially as sea level rises. The Water Board therefore finds that it is in the public interest to encourage beneficial reuse of suitable dredged material as one component of regional adaptation to climate change and reduced suspended sediment loading to the Bay."

(See also, FEIR, Section 3.0, Water Quality, Suspended Sediments/Turbidity.)

The Water Board strives to manage dredged material in the most environmentally-protective manner possible within the limits of its regulatory authority and consistent with the LTMS program goals and disagrees that we have improperly relied on the LTMS EIS/EIR.

Comment 2.I.B: "The Application and TO must conduct a full analysis of ocean dumping criteria…The Regional Board should require the Corps to conduct a complete evaluation to include an analysis of the ocean dumping criteria under the Marine Protection, Research and Sanctuaries Act. (*See* 40 C.F.R. Parts 220-228.)… The Regional Board cannot certify the Project until the Corps conducts a full analysis under 33 C.F.R. part 335.7 and 40 C.F.R. part 227."

Response

We disagree that the Tentative Order is an appropriate regulatory tool to require a full analysis of ocean dumping criteria. The Water Board's jurisdiction is limited to waters within the boundaries of the State, which extend into the Pacific Ocean three geographic miles from the coastline (based on fixed coordinates as of the December 15, 2014, U.S. Supreme Court decision regarding the federal-State boundary, *United States v. State of California* (2014) 135 S.Ct. 563). The deep ocean disposal site, SF-DODS is approximately 55 miles west of the Golden Gate Bridge and is therefore outside the Water Board's jurisdiction. The Tentative Order does not authorize disposal at SF-DODs (see Finding 8).

U.S. EPA possesses the regulatory authority for offshore dredged material disposal. The Marine Protection, Research and Sanctuaries Act (MPRSA) authorizes U.S. EPA to designate permanent ocean-dredged material disposal sites in accordance with specific site selection criteria designed to minimize the adverse effects of ocean disposal of dredged material. Individual ocean disposal suitability determinations are subject to rigorous analysis in accordance with U.S. EPA regulations promulgated to implement MPRSA, and USACE's placement of dredged material at ocean placement sites is subject to episodic approval by U.S. EPA. Under section 103 of MPRSA, U.S. EPA must issue concurrence prior to disposal of dredged material at a designated ocean disposal site such as SF-DODS.

Comment 2.II. "The TO Fails to Adequately Protect Special Status Species… recent abundance numbers for the Delta smelt have been at historic lows and the species is on the brink of extinction. Baykeeper is extremely concerned about the fragile state of this species, and urges the Regional Board to strengthen the conditions in the TO and require that mechanical dredging be phased-in immediately. In particular, waiting to begin the phase-out of hopper dredging until 2017 could result in the imminent extinction of the Delta smelt…The delay of this measure 'due to the Corps' three-year budget process for its operations and maintenance program'(TO at 23) is irrelevant and inconsistent with the purposes of the Endangered Species Act…"

Response
CESA requires that the Board seek to conserve endangered species and use its authority in furtherance of CESA.

In California, the primary resource agency charged with responsibility for and authority regarding endangered species is CDFW. CDFW was consulted at length in the EA/EIR drafting process, and in response to a request for guidance from the Board, provided a memorandum dated March 14, 2014, that outlines conditions and measures CDFW believed would reduce significant impacts to delta and longfin smelt to less than significant. The Tentative Order incorporates all of these conditions.

CDFW received a copy of the Draft EA/EIR as well as the Tentative Order. CDFW commented on the EA/EIR but did not oppose the Tentative Order nor provide any feedback that the two-year delay (intended to reflect USACE's budgetary process) would result in the delta or longfin smelt's extinction. We therefore have not revised the Tentative Order.

As a practical matter, due to the expected government hopper dredges being unavailable due to maintenance/repair work and dredging scheduled in other USACE districts, all in-Bay dredging in 2015, and possibly 2016, is expected to be performed via contractor-provided clamshell dredges, in effect addressing Baykeeper's concerns.

Comment 2.III. "The Final EIR/EA Has Not Been Made Public… Requiring the public to comment on Certification prior to the public release of the FEIR upon which Certification relies is entirely inappropriate and contrary to the public's right to be involved in the environmental review process."

Response
Both the Final EIR and the TO are scheduled for adoption at the May 13, 2015, Board hearing. The Draft EA/EIR and Notice of Availability were published on December 5, 2014, and were available for public review for a 45-day period. While there is no requirement to circulate a final EIR before adoption (Cal. Code Regs., tit. 14, § 15089), the Final EA/EIR, which includes the comments received on the Draft EA/EIR and the Response to Comments (Appendix C), was made publically available online at http://www.waterboards.ca.gov/sanfranciscobay/index.shtml on April 30, 2015, 13 days prior to the Board hearing. Revisions to the Draft EA/EIR were minor in nature.

Comment 2.IV. "The Draft EA/EIR Improperly Defines the 'No Project Alternative.' As stated in the TO, the Draft EA/EIR defines the "No Project Alternative" as the continuation of 'current maintenance dredging practices for the projects it maintains in San Francisco Bay.' …As the

CEQA Guidelines provide, '[t]he purpose of describing and analyzing a no project alternative is to allow decision makers to compare the impacts of approving the proposed project *with the impacts of not approving the proposed project*.' (Guidelines § 15126.6(e)(1) [emphasis added].) Here, a decision to reject the Corps' proposed maintenance dredging project for years 2015 through 2024 would not allow for the continuation of current maintenance dredging projects because the Corps would not have the required permits or approvals to conduct such activities.

Response
We disagree that the Draft EA/EIR improperly defines the "No Project Alternative."

The case of *Center for Biological Diversity v. Department of Fish and Wildlife* (2015) 234 Cal.App.4th 214 is directly on-point and addresses the definition of the "No Project Alternative" applicable to USACE's dredging program. In that case, CDFW had an ongoing fish hatchery and stocking program. CDFW used the existing enterprise from 2004 to 2008 as the "no project" alternative. The Center for Biological Diversity claimed that the appropriate "no project" alternative must be one in which no stocking occurs. Citing Title 14 of the California Code of Regulations, section 15126.6, subdivision (e)(3)(A), the court disagreed, holding that "[u]nder CEQA, where the EIR is reviewing an existing operation or changes to that operation, the no project alternative is the existing operation. Moreover, where a statutory mandate leaves a state agency no discretion to cease or discontinue an existing operation, the no project alternative is the statutorily mandated project." (*Id.* at p. 253.)

In this case, the appropriate no project alternative is USACE's ongoing maintenance dredging activities. Similar to the CDFW authority requiring the existence of the hatchery and stocking program, the Basin Plan requires that the Water Board consider the beneficial use of navigation for the project area. USACE, as mandated by Congress, is responsible for maintaining navigability of federal navigation channels. Maintenance dredging of the federal navigation channels is necessary to provide safe, reliable, and efficient waterborne transportation systems (channels, harbors, and waterways) for the movement of commerce, national security needs, and recreation. A "no maintenance dredging" alternative was rejected because "it would not meet the purpose and need of the project to maintain safe navigation of all the federal navigation channels, and would be expected to have significant economic and safety impacts." (See Final EA/EIR, Section 2.4.1.) "An EIR is not required to consider alternatives which are infeasible." (Cal. Code Regs., tit. 14, § 15126.6, subd. (a).) "Factors that may be used to eliminate alternatives from detailed consideration in an EIR [include] failure to meet most of the basic project objectives." (*Id.* at subd. (c).)

Comment 2.V. "As currently drafted, Baykeeper opposes the TO and urges the Regional Board to deny Certification."

Response
We disagree and recommend adoption of the Tentative Order.

Comment Letter No. 3: California Marine Affairs and Navigation Conference (CMANC)

Comment 3.1: "As the Water Board finds it in the public interest to encourage beneficial reuse of suitable dredged material, please define "beneficial reuse" of dredged material. If this definition does not include placing the material back into San Francisco Bay, please provide the rationale as the Tentative Order comments on significant reduction of sediment loading from the Sacramento-San Joaquin River System."

Response

Use of the term "beneficial reuse" in the Tentative Order is intended to be consistent with the 1998 LTMS EIS/EIR and the 2001Management Plan, which discussed the beneficial reuse of dredged material in broad terms. The intent of these LTMS documents was to avoid unnecessarily restricting known or new potential beneficial reuse opportunities, while providing the public with the assurance that LTMS agencies would only approve projects that clearly offered net environmental benefits. Relevant excerpts from the LTMS EIS/EIR include:

- Section 2.4.2.4 (p. 2 – 18): "'Beneficial reuse' refers to managing dredged material as a valuable resource that can be used to create other benefits, rather than just as a waste product to be disposed of as efficiently as possible."
- Section 2.6.1 (p. 2 – 20): "Proposed habitat restoration projects using dredged material should be evaluated in the context of regional habitat goals developed independently [...] Only habitat restoration/creation projects having positive overall net benefits will be supported as LTMS projects."

The following is a relevant excerpt from the LTMS Management Plan:

- Section ES-7 (p. ES – 17): "For restoration projects using dredged material in areas not covered by regional habitat goals[…] the LTMS agencies will also encourage and authorize as legally appropriate, such projects which would clearly result in an overall net gain in habitat quality and would minimize loss of existing habitat functions. Whenever feasible, such projects will provide, as part of the project design, for a no net loss in the habitat functions existing on the project site or, where necessary, provide compensatory mitigation for lost habitat functions in accordance with state and federal mitigation requirements."

The commenter questions whether unconfined or non-engineered in-Bay placement could be considered beneficial reuse, especially in light of the decrease in suspended sediment supply. The broad definition of beneficial reuse does not preclude placing material back into San Francisco Bay. It must first be demonstrated, however, that 1) there is a need for the reuse project; 2) that the environmental benefits clearly outweigh any environmental impacts or tradeoffs; and 3) that any impacts should be fully mitigated. Several State and federal laws and policies that regulate placement of sediment in aquatic environments would need to be addressed in order to recognize unconfined placement of dredged material in the Bay as a beneficial reuse. In particular, potential impacts to natural resources would need to be evaluated. Currently, no net environmental benefits are associated with placement at existing in-Bay dispersive aquatic disposal sites. These sites were intentionally located in areas of high current energy to maximize dispersal of dredged sediment placed there. Little information currently exists on where waves and currents transport sediment within San Francisco Bay, following an in-Bay dredged material placement. In 2012, as part of the USACE's ongoing

Regional Dredged Material Management Planning process, a three-dimensional hydrodynamic, wave, and sediment transport model was applied to examine sediment dispersal throughout the Bay. One focus of the sediment transport modeling effort was to examine the sediment dispersal following dredged material placements. The model was applied to evaluate sediment dispersal away from two currently designated in-Bay sediment placement sites, Carquinez Strait (SF-9) and San Pablo Bay (SF-10) and two nearby sites adjacent to marsh areas. Model results indicated that placements at these sites, which are in a highly dispersive region, were not effective at supplying sediment to the nearby mudflats and marshes. In contrast, dredged material placement simulations in far South San Francisco Bay demonstrated that the natural dispersal of sediment from open-water in-Bay placements has the potential to be used to augment mudflat, marsh and salt pond sedimentation, but needs further study.

Comment 3.2: "Why not provide a 10-year Water Quality Certification as that was one of the stated purposes of Draft Environmental Assessment/Environmental Impact Report?"

Response

After releasing the Draft EA/EIR, we were informed by the Bay Conservation and Development Commission that its Consistency Determination for the USACE dredging program would cover, at a maximum, a three-year period. We are trying to balance staff resources, considering workloads and the preparation time necessary for multiple Board hearing items for this project during the next 10 years, with the concerns of other agencies involved in regulating USACE dredging. Since the EA/EIR planning period covers 2015 through 2024, we will still be able to use it as the basis for demonstrating compliance with CEQA requirements when considering whether to reissue WDRs and WQC in 2020.

Comment 3.3: "When did the Water Board consider, certify, and approve the final Environmental Impact Report for Federal Navigation Channels?"

Response

The Water Board is considering the Final Environmental Impact Report for certification at the May 13, 2015, public hearing. This item will immediately precede consideration of the Tentative Order.

Comment 3.4: "In order to provide clarity, please define San Francisco Bay and Central Bay as the terms are used in the Tentative Order. One of the [hopper dredging] projects is outside of the Bay, another is in San Pablo Bay and a third is in Suisun Bay."

Response

San Francisco Bay is a broad term inclusive of all the various sub-embayments (Suisun Bay, San Pablo Bay, Central Bay, South Bay, and Lower South Bay). There are only two places in the Tentative Order that use the term "Central Bay" in relation to USACE dredging projects, Finding 18g and Provision 12g, which are identical. We have revised Finding 18g and Provision 12g in response to the comment as follows:

g. Completing hydraulic dredging in Central Bay <u>(i.e., Richmond Outer Harbor)</u> between August 1 and November 30 to avoid impacts to young-of-the-year and spawning adult longfin smelt.

Comment 3.5: "Page 7, foot note *is this inner or outer?"

Response
The footnote refers to Richmond Outer Harbor. The word "Inner" has been deleted and replaced with "Outer" in the Tentative Order.

Comment 3.6: "Please provide a copy of the March 14, 2014 CDFW Letter referenced in the Tentative Order."

Response
The CDFW memorandum has been included as an attachment to the Tentative Order (Item 8 on the May 13, 2015 agenda), which is available online at http://www.waterboards.ca.gov/sanfranciscobay/board_info/agendas/2015/May/5_13_Agenda.pdf.

Comment 3.7: "Hydraulic dredging includes hopper dredging and cutter head dredging. The Tentative Order wants to reduce hopper dredging and yet uses terms such as cutter heads, hydraulic suction hopper dredging, hopper dredging, and hydraulic dredging. Is the Tentative Order restricting all hydraulic dredging or just hopper dredging? This should be clarified as the Draft EA/EIR did discuss the distinction between hopper and cutter head dredging as it relates to entrainment."

Response
Provision 10 "Phased-In Reduction of Hydraulic Suction Hopper Dredging inside San Francisco Bay," which restricts the type of dredge equipment used in order to protect special status fish species, **clearly** refers to hydraulic suction hopper dredging and no other type of dredging. The key words are "hopper dredging," which refer to a specific type of hydraulic dredging performed by self-propelled seagoing vessels designed to dredge and transport material in a hopper bin on board the dredge from navigation channels to open-water disposal areas. We see no ambiguity in Provision 10.

The term "hydraulic dredging," which is used in the list of avoidance, minimization, and mitigation measures for entrainment impacts in Finding 18 and Provision 12, is inclusive of all types of hydraulic suction dredging, including both hopper and cutterhead dredges. Because Findings 18f and 18g and Provisions 12f and 12g were intended to apply to hopper dredging, we have revised Finding 18f and Provision 12f, which are identical, in response to the comment as follows:

f. Completing hydraulic <u>hopper</u> dredging in Suisun Bay between August 1 and September 30, to avoid impacts to spawning adult longfin and delta smelt.

Similarly, we have revised Finding 18g and Provision 12g, which are identical, in response to the comment as follows:

g. Completing hydraulic <u>hopper</u> dredging in Central Bay (i.e., Richmond Outer Harbor) between August 1 and November 30 to avoid impacts to young-of-the-year and spawning adult longfin smelt.

Comment 3.8: "Based on the Draft EA/EIR there is a ten to one ratio between mechanical dredging and hopper dredging in the time needed to dredge certain channels. The Tentative Order does not show that the Water Board considered any adverse impacts, such as noise, that may result to various aquatic species by these longer dredge times. Did they? We believe their consideration or lack of consideration should be discussed in the Tentative Order."

Response

As a point of clarification, the Draft EA/EIR (DEIR) cites a study performed by USACE concluding that dredging with a clamshell bucket dredge can take "up to" ten times longer than dredging with a hopper dredge. The impacts of Reduced Hopper Dredge Use Alternatives 1 and 2 were fully analyzed in the DEIR and final EIR, and no significant impacts related to an increased length of time necessary to complete dredging via clamshell bucket dredges were identified. The Tentative Order considered all impacts that were determined to be significant under CEQA (Finding 20, pages 14-17).

Comment 3.9: "We request the Water Board positively affirm that additional sediment does not need to go into the water column as the Tentative Order does state "Less sediment in suspension and circulation within the Bay impairs the ability of shorelines, mudflats, and tidal wetlands to withstand erosion and inundation, especially as sea level rises. As we see the question, under current Sea Level Rise predictions from the State of California (up to 5.48 feet by the year 2100), is it better to put dredged material back into the Bay where it will increase sediment in suspension and possibly feed both mudflats and wetlands or place the sediment directly into wetlands that may or may not be able to function under Sea Level Rise and possibly not provide other benefits, such as limiting the loss of mudflats?"

Response

We cannot make the affirmation requested. There may be specific circumstances under which placement of sediment "into the water column" can be demonstrated to provide a net environmental benefit. A project proponent would first have to meet the criteria listed in the response to Comment 3.1 and demonstrate that sediment placed in the Bay measurably increases the elevation of mudflat or wetland habitat before we would consider in-Bay placement to be of equal or greater benefit than direct placement into wetlands.

Comment 3.10: "While the Draft EA/EIR discusses the impact of not receiving sufficient funds for the Corps to perform the maintenance dredging under Alternative 1 and 2. It only discussed the potential impacts to those navigation channels. The most likely scenario, based on the increased funding to Oakland and Richmond over the past several years, is that other projects within San Francisco Bay or along the Coast of California will not receive sufficient funding for adequate maintenance dredging. Please state that the Water Board has reviewed the socio economic, life safety and environmental impacts to other Corps' projects within the San Francisco District and South Pacific Division due to the additional costs of dredging navigation channels in San Francisco Bay as a result of this Tentative Order. Specifically, dredging of small coastal communities such as: Moss Landing; Noyo and Morro Bay."

Response

The Board has crafted the Tentative Order taking into account USACE's budget process and allowing sufficient time for USACE to obtain sufficient funding to avoid any reallocation of existing funds. To the extent that USACE chooses not to ask for an increase in funding and/or chooses to reallocate existing funds from other projects, the Board does not have any control over USACE's internal budgetary process.

Comment Letter No. 4: R.E. Staite Engineering, Inc. (R.E. Staite)

All comments are related to the overflow/decant discharge monitoring plan required in Provision 6 of the Tentative Order.

Comment 4.1: "Please delete 'an overflow' monitoring plan and replace it with 'a decanting' monitoring plan."

Response
Both terms have sometimes been used interchangeably in the past by both regulators and dredgers. We have revised the text to read "…an overflow or decanting monitoring plan…"

Comment 4.2: "Regarding the limits for turbidity, a ten percent above background level is a very difficult standard to meet. The practical impact of this standard is that it is highly likely that a ten percent above background level will trigger multiple work stoppages. Our experience has shown (as well as a recent ACOE study) that dredging turbidity plumes rapidly dissipate. Our primary concern is that as presently drafted, the Tentative Order could result in routine work stoppages or significant slowdowns of dredging activities because the monitoring benchmark is just slightly above background levels."

Response
Provision 6 does not mandate work stoppages for exceedance of the turbidity objective. It does require that the monitoring plan USACE submits include "a contingency plan in the event of an observed exceedance of one or more water quality objectives." An example of a contingency plan that does not involve work stopping would be to take more frequent turbidity measurements to determine how quickly turbidity dissipates.

Comment 4.3: "Another factor that should be considered when setting turbidity limits includes the location of the monitoring station. Having sampling stations located too close to the dredging activities can further exacerbate a ten percent above background limit. In order to reduce 'false alarms', we recommend sampling at a distance of 600' only, which is the 'point of compliance.'"

Response
We will take siting of monitoring locations and the potential for "false alarms" into consideration on a project-by-project basis when reviewing the monitoring plans submitted by USACE. As stated in Provision 6, the location of monitoring stations is also dependent on the distance to sensitive habitat, such as eelgrass beds, which may be less than 600 feet from dredging activity in some of the federal channels.

Comment 4.4: "A factor not considered in the above condition is the effect of tug boat operations during monitoring activities. In some locations and tidal conditions, tug boats can create turbidity. If sampling occurs during or after tug boat operations, false readings may be received. Therefore, we recommend that no sampling occur during tug boat operations and that sampling also be delayed until tug associated turbidity has cleared. We request that the above tug boat operational factors are made a condition precedent to gathering turbidity data."

Response
We will take this factor into consideration when reviewing the sample collection protocol section of the monitoring plans that USACE submits pursuant Provision 6.

Comment 4.5: "Please adopt the following:

- ***Turbidity $\leq$ 50 NTU (or up to ~~10~~ 20 percent greater than turbidity at a background reference location sampled concurrently with the dredging location, if the background turbidity is greater than 50 NTU).***
- ***Monitor sampling locations shall be located at the "point of compliance," or at least 600' from the dredging activities.***
- ***Sampling shall not occur until any turbidity from tug activity clears.*"**

Response
Please refer to responses to Comments 4.2, 4.3, and 4.4.

Comment 4.6: "The concerns above also apply to dissolved oxygen (DO) monitoring levels. Again, it is highly likely that the combination of 'just above background levels' and near-by monitoring stations will trigger contingency plans that will significantly impact dredging operations. Please include a 20-percent decrease from background DO levels. The revised text would read: *Dissolved oxygen $\geq$ 5.0 mg/L ($\geq$ 7.0 mg/L east of the Carquinez Bridge), or a 20-percent decrease from background DO levels.*"

Response
The Basin Plan water quality objective for DO is as stated in the Tentative Order. A "20-percent decrease from background DO levels" is not in included in the Basin Plan objective. We have not revised the receiving water limit for DO in Tentative Order.

Comment 4.7: "Based on our most recent project data, it should be noted that 35% - 45% of a fully loaded scow (if not decanted) is comprised of bay water. The amount of water retained depends on the type of sediments at the project site and the type of bucket used for the operation. While the total number of disposal trips and trips saved could be estimated for each project based on the estimated production rate and the equipment planned for the project, it should be recognized that any reduction in total trips to a disposal site would be of benefit to the environment. It is suggested that the item #2 requirements [shown below] be deleted."

> ***2) Describe how the effectiveness of economic barge loading, i.e. total cubic yards of material placed into a scow, vs. amount of suspended sediment released to the Bay will be evaluated with and without overflow***

Response
The component of the monitoring plan required in Provision 6 and referenced in the comment was intended to compare the increase in suspended sediment in the water column during overflow vs. non-overflow conditions. This can be incorporated into the first component of the monitoring plan. We deleted the language as requested by the Commenter. The text quoted in the comment above has been revised to read:
:

> "In addition, the monitoring plan shall: 1) describe how the temporal and spatial extent of the suspended sediment plume associated with overflow/decant discharge will be characterized *and compared to non-overflow conditions*; 2) describe reporting format and frequency; and 3) include a contingency plan in the event of an observed exceedance of one or more water quality objectives caused by overflow/decant discharges."

Comment 4.8: R.E. Staite is concerned that requiring monitoring plan submittal a minimum of 90 days prior to dredging does not allow enough time incorporate monitoring into USACE dredging contract specifications and get Water Board approval before dredging is scheduled to start. R.E. Staite recommends "that a 'master monitoring plan' be produced that could be incorporated into the ACOE's [USACE's] bidding processes." R.E. Staite also requests that "every effort be made to approve a monitoring plan prior to ACOE [USACE] project bid dates to give contractors adequate time to include monitoring costs in their final bid pricing package."

Response
We agree that receiving a monitoring plan earlier in the project planning process is beneficial for everyone involved. We support preparation of a master monitoring plan from which project-specific plans can be tiered, and we will encourage USACE's efforts in this direction. We will promptly review the plans that USACE submits and, if they are acceptable, approve them.

Comment 4.9: "It is our understanding that the ACOE is in the process of preparing a decanting monitoring plan. Since this process is in its early stages of development, we request that the following be included in any follow-up monitoring plan that is adopted:

<u>Plan Requirement</u>
The monitoring plan requirement should be rescinded after two years/seasons if previous project monitoring data demonstrates little to no increases above background levels of turbidity, DO, or pH.

<u>Monitoring Frequency</u>
Sampling should be reduced to weekly sampling if no water quality exceedances are observed after 3 consecutive days of monitoring.

<u>Testing Locations</u>
The only monitoring station needed is at the point of compliance; 600' from the dredging operation.

<u>Turbidity Testing Within the Water Column</u>
Our concern is that taking samples near the bottom of the bay (-2" from the bay bottom) will fail to provide any meaningful data. At the bottom of the bay there are many factors that can increase turbidity such as tides and currents. These natural forces will compromise the samples taken and not yield meaningful data. Therefore we recommend that any monitoring plan only include surface samples and a mid-level water column sample.

<u>Contingencies for Exceedance</u>
Please adopt alternatives other than dredging stoppages or slowdowns should there be background level exceedences. Alternatives to work stoppage may include re-testing or consultations and notifications to the USAGE and/or RWQCB staff.

Monitoring Flow Chart
A Monitoring Flow Chart was prepared for the San Diego Bay Environmental Restoration North Trust North Shipyard Project by Anchor QEA. The flow chart is attached as an example of how a master monitoring plan could be sequenced and implemented."

Response
Comment noted. We will take R.E. Staite's recommendations into consideration when reviewing the monitoring plans that USACE submits.

Comment Letter No. 5: Port of Redwood City

Comment 5.1: "Figure 7, page 36, shows the Redwood City Channel. The purple shaded disposal site is the San Leandro Marina disposal site. I believe the figure should reference the SF-11 site typically used."

Response
SF-11 is outside the boundary of Figure 7 showing the Redwood City Channel. To see the location of SF-11, please refer to Figure 1, which shows all the dredged material placement sites in relation to the federal channel locations. We have deleted the San Leandro Dredged Material Disposal Site from Figure 7.

Staff-Initiated Changes

We corrected typographical errors and made other minor editorial and formatting changes to the Tentative Order.

In addition, we revised the measure to minimize impacts to longfin smelt and delta smelt described in Finding 18h and Provision 12h to be consistent with the Final EA/EIR as follows:

h. ~~Monitoring~~ Maintaining contact of drag head, cutterheads, and pipeline intakes ~~so that they maintain contact~~ with the seafloor during suction dredging.