California State Waters Map Series—Offshore of San Francisco, California

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(Guy R. Cochrane and Susan A. Cochran, editors)

Pamphlet to accompany

Open-File Report 2015–1068

2015

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

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Suggested citation:
Cochrane, G.R., Johnson, S.Y., Dartnell, P., Greene, H.G., Erdey, M.D., Golden, N.E., Hartwell, S.R., Endris, C.A., Manson, M.W., Sliter, R.W., Kvitek, R.G., Watt, J.T., Ross, S.L., and Bruns, T.R. (G.R. Cochrane and S.A. Cochran, eds.), 2015, California State Waters Map Series—Offshore of San Francisco, California: U.S. Geological Survey Open-File Report 2015–1068, pamphlet 39 p., 10 sheets, scale 1:24,000, http://dx.doi.org/10.3133/ofr20151068.

ISSN 2331-1258 (online)

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(Guy R. Cochrane[1] and Susan A. Cochran,[1] editors)

Preface

In 2007, the California Ocean Protection Council initiated the California Seafloor Mapping Program (CSMP), designed to create a comprehensive seafloor map of high-resolution bathymetry, marine benthic habitats, and geology within California's State Waters. The program supports a large number of coastal-zone- and ocean-management issues, including the California Marine Life Protection Act (MLPA) (California Department of Fish and Wildlife, 2008), which requires information about the distribution of ecosystems as part of the design and proposal process for the establishment of Marine Protected Areas. A focus of CSMP is to map California's State Waters with consistent methods at a consistent scale.

The CSMP approach is to create highly detailed seafloor maps through collection, integration, interpretation, and visualization of swath sonar data (the undersea equivalent of satellite remote-sensing data in terrestrial mapping), acoustic backscatter, seafloor video, seafloor photography, high-resolution seismic-reflection profiles, and bottom-sediment sampling data. The map products display seafloor morphology and character, identify potential marine benthic habitats, and illustrate both the surficial seafloor geology and shallow (to about 100 m) subsurface geology. It is emphasized that the more interpretive habitat and geology maps rely on the integration of multiple, new high-resolution datasets and that mapping at small scales would not be possible without such data.

This approach and CSMP planning is based in part on recommendations of the Marine Mapping Planning Workshop (Kvitek and others, 2006), attended by coastal and marine managers and scientists from around the state. That workshop established geographic priorities for a coastal mapping project and identified the need for coverage of "lands" from the shore strand line (defined as Mean Higher High Water; MHHW) out to the 3-nautical-mile (5.6-km) limit of California's State Waters. Unfortunately, surveying the zone from MHHW out to 10-m water depth is not consistently possible using ship-based surveying methods, owing to sea state (for example, waves, wind, or currents), kelp coverage, and shallow rock outcrops. Accordingly, some of the maps presented in this series commonly do not cover the zone from the shore out to 10-m depth; these "no data" zones appear pale gray on most maps.

This map is part of a series of online U.S. Geological Survey (USGS) publications, each of which includes several map sheets, some explanatory text, and a descriptive pamphlet. Each map sheet is published as a PDF file. Geographic information system (GIS) files that contain both ESRI[5] ArcGIS

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raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed September 20, 2013).

The California Seafloor Mapping Program is a collaborative venture between numerous different federal and state agencies, academia, and the private sector. CSMP partners include the California Coastal Conservancy, the California Ocean Protection Council, the California Department of Fish and Wildlife, the California Geological Survey, California State University at Monterey Bay's Seafloor Mapping Lab, Moss Landing Marine Laboratories Center for Habitat Studies, Fugro Pelagos, Pacific Gas and Electric Company, National Oceanic and Atmospheric Administration (NOAA, including National Ocean Service–Office of Coast Surveys, National Marine Sanctuaries, and National Marine Fisheries Service), U.S. Army Corps of Engineers, the Bureau of Ocean Energy Management, the National Park Service, and the U.S. Geological Survey.

Chapter 1. Introduction

By Guy R. Cochrane

Regional Setting

The map area offshore of San Francisco, California, which is referred to herein as the “Offshore of San Francisco” map area (figs. 1–1, 1–2) is centered on the Golden Gate, the inlet of the San Francisco Bay. The San Francisco Bay Area is the second-largest urban area on the U.S. West Coast with a combined population of over seven million. The San Francisco Bay supports several major cargo ports; over one million metric tons of cargo was off-loaded at the port of San Francisco in 2011. The Port of San Francisco’s Fisherman’s Wharf is a major center for Northern California’s commercial and sport fishing fleets. The Wharf’s Pier 45 houses the largest concentration of commercial fish processors and distributors on the West Coast. Dungeness crab, California halibut, and Pacific salmon fisheries rely on the bay as a nursery. There are numerous recreational harbors in San Francisco Bay and sailing is popular (boats, as well as windsurfing and kitesurfing) because of consistent strong westerly-northwesterly winds of 15–25 knots and protection from large open-ocean swells.

Before urbanization and the start of the Gold Rush in 1849, the San Francisco Bay contained extensive wetlands that graded from freshwater wetlands to salt marshes to tidal mudflats (Nichols and others, 1986). An underwater channel within a sea-level-drowned river valley runs from southeast to northwest through the center of the bay (Atwater, 1979). Hydraulic mining for gold extraction in the Sierra Nevada in the middle to late 1800s displaced large sediment volumes that were carried into the Bay by the San Joaquin and Sacramento rivers, greatly reducing the water depth in the Bay (Gilbert, 1917). Dredging was necessary to maintain shipping channels and continues into the present day. The Golden Gate channel is the sole tidal inlet that connects San Francisco Bay to the Pacific Ocean. Tidal currents accelerate through the narrow passage of the Golden Gate and scour sediment from the seafloor. The currents decelerate as the strait widens at either end, depositing sand and gravel to form one of the largest sand-wave fields in the world (Barnard and others, 2012). Offshore, the sand wave field grades into a large ebb-tide delta composed of sand with smaller sand waves and ripples.

The western margin of North America is the only continental margin in the world delineated largely by transform faults such as the San Andreas (Dickinson, 2004). The San Francisco and Marin Peninsulas are uplifted terranes to the east of the San Andreas Fault Zone (SAFZ) and the San Gregorio Fault Zone (SGFZ). Coastal geomorphology is controlled by late Pleistocene to Holocene fault slip in the SAFZ (Dickinson and others, 2005). Eastward transfer of right-lateral slip in a complex of faults northwest of the map area has caused extension offshore and the formation of a sediment basin on the continental shelf (Ryan and others 2008). The accommodation space created by extension on the shelf and the proximity to sediment transported to the ocean through San Francisco Bay results in a sand-dominated offshore shelf environment.

With the exception of the Ocean Beach area in San Francisco, the coast consists of high coastal bluffs and vertical sea cliffs (Griggs and others, 2005). Local erosion of sea cliffs also contributes sediment to the nearshore environment. Coastal sediment transport in the Offshore of San Francisco map area is characterized by north-to-south littoral transport of sediment (Hapke and others, 2006). Despite the likely presence of a river valley connecting the Sacramento and San Joaquin rivers to the ocean during the last low sea-level stand, no canyon incises the shelf today. Also, no major canyons extend beyond the shelf break into the nearshore zone to receive littoral drift. Offshore beyond California’s State Waters, unnamed canyons that incise the slope have been disconnected from coastal streams by changing sea level which has risen about 125 m since the lowstand associated with the last glacial maximum (LGM) about 18,000 to 20,000 years ago (Fairbanks, 1989; Fleming and others, 1998;

Lambeck and Chappell, 2001; Lambeck and others, 2002). Griggs and others (2005) categorize most coastline erosion in the map area north of the Golden Gate as high risk, with the exception of Muir Beach and Rodeo Cove areas where cliffs are lacking. Offshore of the City of San Francisco, coastal erosion has been significant in the Ocean Beach area. Anthropogenic influences in San Francisco Bay have reduced the sediment supply from the Bay to the nearshore ebb-tide delta offshore of Ocean Beach (Barnard and others, 2012). A seawall protects a portion of Ocean Beach.

Benthic species observed in the Offshore of San Francisco map area are natives of the cold-temperate biogeographic zone named either the “Oregonian province” (Briggs, 1974) or the “northern California ecoregion” (Spalding and others, 2007). This biogeographic province is maintained by the long-term stability of the southward-flowing California Current, an eastern limb of the North Pacific subtropical gyre that flows from Oregon to Baja California. At its midpoint offshore of central California, the California Current transports subarctic surface (0–500 m deep) waters southeastward, about 150 to 1,300 km from shore (Lynn and Simpson, 1987; Collins and others, 2000). Seasonal northwesterly winds (Inman and Jenkins, 1999) that are, in part, responsible for the California Current, generate coastal upwelling. The south end of the Oregonian province is at Point Conception (about 365 km south of the map area), although its associated phylogeographic group of marine fauna may extend beyond to the area offshore of Los Angeles in southern California (Dawson and others, 2006). Ocean temperatures offshore of central California have increased over the past 50 years, driving an ecosystem shift from the productive subarctic regime towards a depopulated subtropical environment (McGowan and others, 1998).

Seafloor habitats in the Offshore of San Francisco map area lie within the Shelf (continental shelf) megahabitat or the Inland Seas class of Greene and others (1999) and comprise significant sand-dominated sediment habitat with sand wave and ripple bedforms indicative of high wave and current energy. North of the Golden Gate, biological productivity resulting from coastal upwelling supports populations of Sooty Shearwater (*Puffinus griseus*), Western Gull (*Larus occidentalis*), Common Murre (*Uria aalge*), Cassin’s Auklet (*Ptychoramphus aleuticus*), and many other less populous bird species (Ainley and Hyrenbach, 2010). In addition, an observable recovery of Humpback and Blue Whales (*Megaptera novaeangliae* and *Balaenoptera musculus*, respectively) has occurred in the area; both species are dependent on coastal upwelling to provide nutrients (Calambokidis and Barlow, 2004). For the first time in 65 years, Pacific Harbor Porpoise (*Phocoena phocoena*) returned to San Francisco Bay in 2009. On the coast north of the Golden Gate, the large extent of exposed inner shelf bedrock supports large forests of “bull kelp” (*Nereocystis luetkeana*) (Miller and Estes, 1989), which is well adapted for high wave-energy environments (Koehl and Wainwright, 1977). Common fish species found in the kelp beds and rocky reefs include blue rockfish (*Sebastes mystinus*), black rockfish (*Sebastes melanops*), olive rockfish (*Sebastes serranoides*), kelp rockfish (*Sebastes atrovirens*), gopher rockfish (*Sebastes carnatus*), black-and-yellow rockfish (*Sebastes chrysomelas*), painted greenling (*Oxylebius pictus*), kelp greenling (*Hexagrammos decagrammus*), and lingcod (*Ophiodon elongatus*) (Stephens and others, 2006).

Publication Summary

This publication about the Offshore of San Francisco map area includes ten map sheets that contain explanatory text, in addition to this descriptive pamphlet and a data catalog of geographic information system (GIS) files. Sheets 1, 2, and 3 combine data from four different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data reveal a range of physiographic features (highlighted in the perspective views on sheet 4) including exposed bedrock outcrops, large fields of sand waves, as well as many human impacts on the seafloor. To validate geological and biological interpretations of the sonar data shown in sheets 1, 2, and

3, the U.S. Geological Survey towed a camera sled over specific offshore locations, collecting both video and photographic imagery; these “ground-truth” surveying data are summarized on sheet 6. Sheet 5 is a “seafloor character” map, which classifies the seafloor on the basis of depth, slope, rugosity (ruggedness), and backscatter intensity and which is further informed by the ground-truth-survey imagery. Sheet 7 is a map of “potential habitats,” which are delineated on the basis of substrate type, geomorphology, seafloor process, or other attributes that may provide a habitat for a specific species or assemblage of organisms. Sheet 8 compiles representative seismic-reflection profiles from the map area, providing information on the subsurface stratigraphy and structure of the map area. Sheet 9 shows the distribution and thickness of young sediment (deposited over the past about 21,000 years, during the most recent sea-level rise) in both the map area and the larger Bolinas to Pescadero region, interpreted on the basis of the seismic-reflection data. Sheet 10 is a geologic map that merges onshore geologic mapping (compiled from existing maps by the California Geological Survey) and new offshore geologic mapping that is based on integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

The information provided by the map sheets, pamphlet, and data catalog has a broad range of applications. High-resolution bathymetry, acoustic backscatter, ground-truth-surveying imagery, and habitat mapping all contribute to habitat characterization and ecosystem-based management by providing essential data for delineation of marine protected areas and ecosystem restoration. Many of the maps provide high-resolution baselines that will be critical for monitoring environmental change associated with climate change, coastal development, or other forcings. High-resolution bathymetry is a critical component for modeling coastal flooding caused by storms and tsunamis, as well as inundation associated with longer term sea-level rise. Seismic-reflection and bathymetric data help characterize earthquake and tsunami sources, critical for natural-hazard assessments of coastal zones. Information on sediment distribution and thickness is essential to the understanding of local and regional sediment transport, as well as the development of regional sediment-management plans. In addition, siting of any new offshore infrastructure (for example, pipelines, cables, or renewable-energy facilities) will depend on high-resolution mapping. Finally, this mapping will both stimulate and enable new scientific research and also raise public awareness of, and education about, coastal environments and issues.

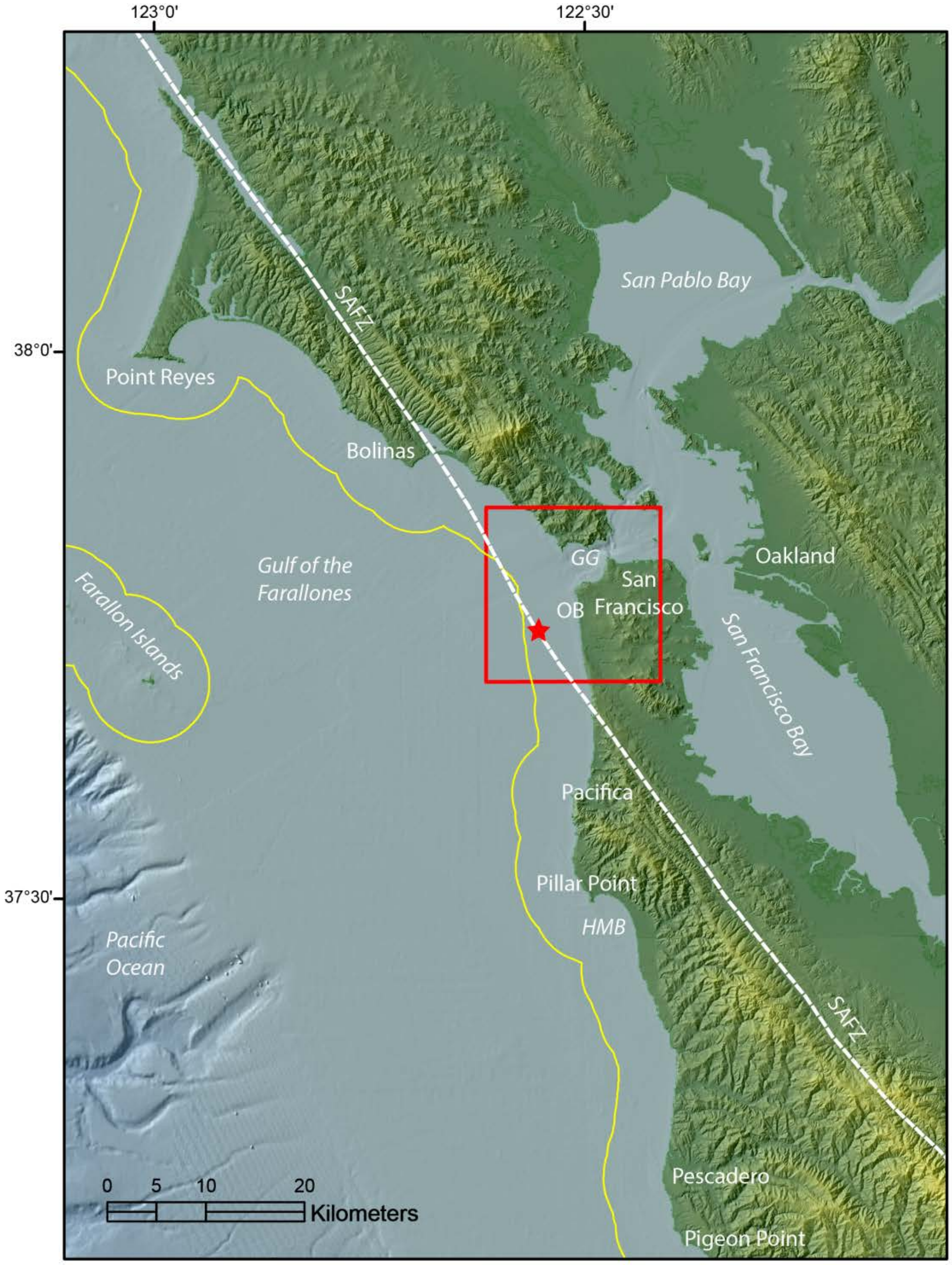

Figure 1–1. Physiography of Bolinas to Pescadero region and its environs. Box shows Offshore of San Francisco map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Red star shows epicenter of great 1906 California earthquake. Other abbreviations: GG, Golden Gate; HMB, Half Moon Bay; OB, Ocean Beach.

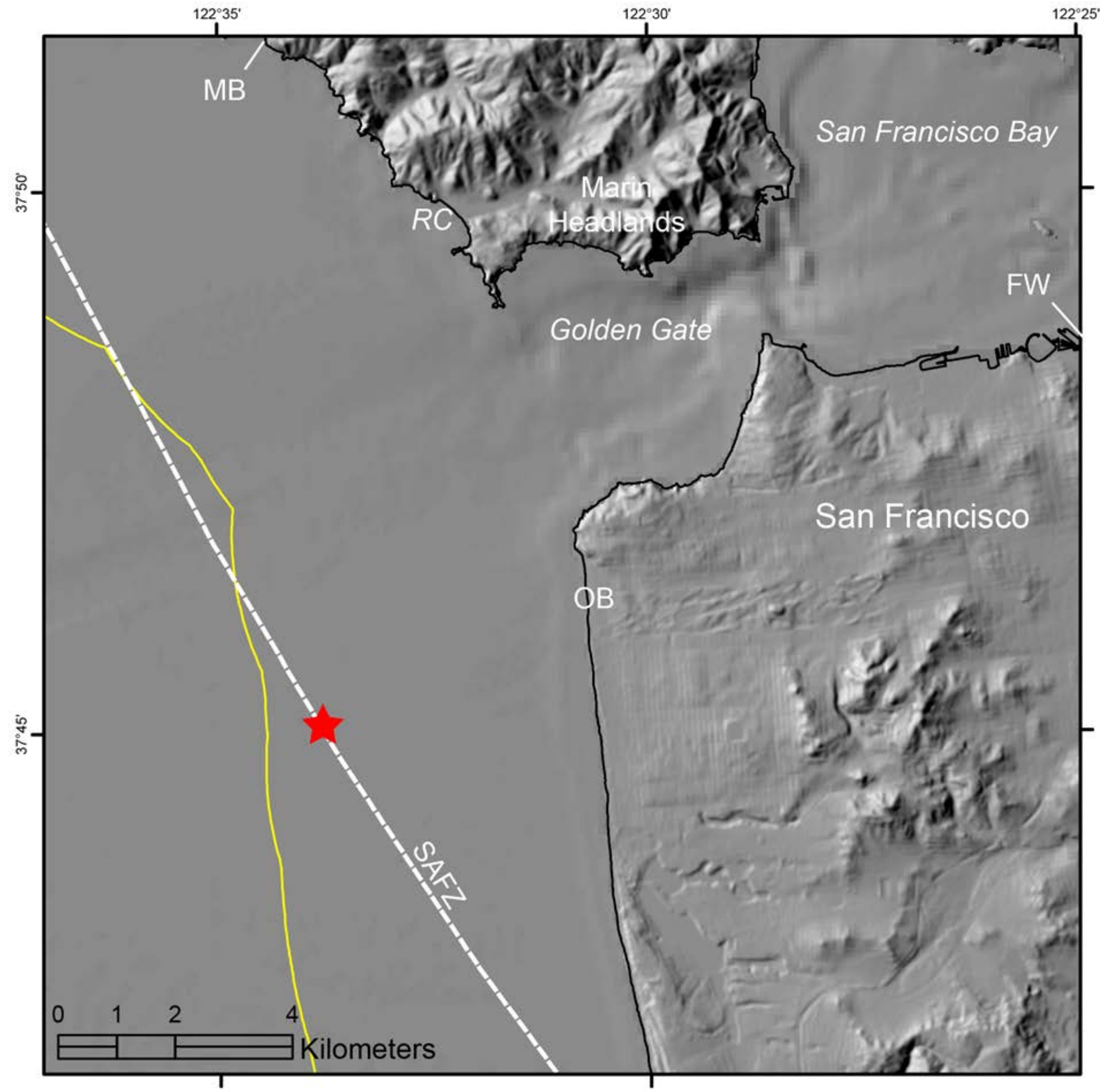

Figure 1–2. Coastal geography of Offshore of San Francisco map area. Solid yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Red star shows epicenter of great 1906 California earthquake. Other abbreviations: FW, Fisherman's Wharf; MB, Muir Beach; OB, Ocean Beach; RC, Rodeo Cove.

Chapter 2. Bathymetry and Backscatter-Intensity Maps of the Offshore of San Francisco Map Area (Sheets 1, 2, and 3)

By Peter Dartnell and Rikk G. Kvitek

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of San Francisco map area in northern California were generated from bathymetry and backscatter data collected by California State University, Monterey Bay (CSUMB) and by Fugro Pelagos (fig. 1 on sheets 1, 2, 3). Most of the area was mapped by CSUMB in 2004, 2005, 2007, and 2008; a small offshore portion near the southern boundary of the map area was mapped by Fugro Pelagos in 2006. Both used a combination of 400-kHz Reson 7125 and 244-kHz Reson 8101 multibeam echosounders. These mapping missions combined to collect both bathymetry (sheets 1, 2) and acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 3-nautical-mile limit of California's State Waters. A large portion of this map area was re-mapped in 2009, however, older bathymetry data were used to create map sheets 1 and 2 due to the co-registered, acoustic-backscatter data (sheet 3).

During all the mapping missions, an Applanix POS MV (Position and Orientation System for Marine Vessels) was used to accurately position the vessels during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm). To account for tidal-cycle fluctuations, CSUMB used NavCom 2050 GPS receiver (CNAV) data, and Fugro Pelagos used KGPS data (GPS data with real-time kinematic corrections); in addition, sound-velocity profiles were collected with an Applied Microsystems (AM) SVPlus sound velocimeter. Soundings were corrected for vessel motion using the Applanix POS MV data, for variations in water-column sound velocity using the AM SVPlus data, and for variations in water height (tides) using vertical-position data from the KGPS receivers. Backscatter data were postprocessed using Geocoder version 3.2 (Fugro Pelagos modified test release 16). Within Geocoder, the backscatter intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. After the lines were corrected, they were mosaicked into 1- and 2-m-resolution images. Overlap between parallel lines was resolved using a priority table whose values were based on the distance of each sample from the ship track, with the samples that were closest to and furthest from the ship track being given the lowest priority. An anti-aliasing algorithm was also applied. The mosaics were then exported as georeferenced TIFF images, imported into a geographic information system (GIS), and converted to GRIDs at 2-m resolution.

Processed soundings from the different mapping missions were exported from the acquisition or processing software as XYZ files and bathymetric surfaces. All the surfaces were merged into one overall 2-m-resolution bathymetric-surface model and clipped to the boundary of the map area. An illumination having an azimuth of 300° and from 45° above the horizon was then applied to the bathymetric surface to create the shaded-relief imagery (sheets 1, 2). In addition, a modified "rainbow" color ramp was applied to the bathymetry data for sheet 1, using reds and oranges to represent shallower depths, and blues and purples to represent greater depths. This colored bathymetry surface was draped over the shaded-relief imagery at 60-percent transparency to create a colored shaded-relief map (sheet 1).

Bathymetric contours (sheets 1, 2, 3, 5, 7, 10) were generated at 10-m intervals from the merged 2-m-resolution bathymetric surface. The most continuous contour segments were preserved; smaller segments and isolated island polygons were excluded from the final output. Contours were smoothed using a polynomial approximation with an exponential kernel algorithm and a tolerance value of 60 m.

The backscatter grids were combined in a GIS to create an acoustic-backscatter map (sheet 3), on which brighter tones indicate higher backscatter intensity, and darker tones indicate lower backscatter intensity. The intensity represents a complex interaction between the acoustic pulse and the seafloor, as well as characteristics within the shallow subsurface, providing a general indication of seafloor texture and sediment type. Backscatter intensity depends on the acoustic source level; the frequency used to image the seafloor; the grazing angle; the composition and character of the seafloor, including grain size, water content, bulk density, and seafloor roughness; and some biological cover. Harder and rougher bottom types such as rocky outcrops or coarse sediment typically return stronger intensities (high backscatter, lighter tones), whereas softer bottom types such as fine sediment return weaker intensities (low backscatter, darker tones).

The onshore-area image was generated by applying an illumination having an azimuth of 300° and from 45° above the horizon to topographic-lidar data collected by Earth Eye in 2010 for San Francisco State University and the U.S. Geological Survey.

Chapter 3. Data Integration and Visualization for the Offshore of San Francisco Map Area (Sheet 4)

By Peter Dartnell

Mapping California's State Waters has produced a vast amount of acoustic and visual data, including bathymetry, acoustic backscatter, seismic-reflection profiles, and seafloor video and photography. These data are used by researchers to develop maps, reports, and other tools to assist in the coastal and marine spatial-planning capability of coastal-zone managers and other stakeholders. For example, seafloor-character (sheet 5), habitat (sheet 7), and geologic (sheet 10) maps of the Offshore of San Francisco map area may assist in the designation of Marine Protected Areas, as well as in their monitoring. These maps and reports also help to analyze environmental change owing to sea-level rise and coastal development, to model and predict sediment and contaminant budgets and transport, to site offshore infrastructure, and to assess tsunami and earthquake hazards. To facilitate this increased understanding and to assist in product development, it is helpful to integrate the different datasets and then view the results in three-dimensional representations such as those displayed on the data integration and visualization sheet for the Offshore of San Francisco map area (sheet 4).

The maps and three-dimensional views on sheet 4 were created using a series of geographic information systems (GIS) and visualization techniques. Using GIS, the bathymetric and topographic data (sheet 1) were converted to ASCIIRASTER format files, and the acoustic-backscatter data (sheet 3) were converted to geoTIFF images. The bathymetric and topographic data were imported in the Fledermaus® software (QPS). The bathymetry was color-coded to closely match the colored shaded-relief bathymetry on sheet 1 in which reds and oranges represent shallower depths and blues and purples represent deeper depths. Digital orthophotographs were draped over the topography data, and the acoustic-backscatter geoTIFF images were draped over the bathymetry data. The colored bathymetry, topography, and draped backscatter were then tilted and panned to create the perspective views such as those shown in figures 1, 2, 3, 4, 5, and 6 on sheet 4. These views highlight the morphology within San Francisco Bay and offshore of the Golden Gate, including exposed bedrock outcrops, large fields of sand waves, and many human impacts on the seafloor.

Block diagrams that combine the bathymetry with seismic-reflection-profile data help integrate surface and subsurface observations, especially stratigraphic and structural relations (for example, fig. 6 on sheet 4). These block diagrams were created by converting digital seismic-reflection-profile data (see sheet 8) into TIFF images, while taking note of the starting and ending coordinates and maximum and minimum depths. The images were then imported into the Fledermaus® software as vertical images and merged with the bathymetry imagery.

While most of the California Seafloor Mapping Program, Data Integration and Visualization sheets include video mosaics generated from digital seafloor video, the Data Integration and Visualization sheet for the Offshore of San Francisco map area does not include a video mosaic due to poor water clarity at the time of the video ground-truthing.

Chapter 4. Seafloor-Character Map of the Offshore of San Francisco Map Area (Sheet 5)

By Mercedes D. Erdey and Guy R. Cochrane

The California State Marine Life Protection Act (MLPA) calls for protecting representative types of habitat in different depth zones and environmental conditions. A science team, assembled under the auspices of the California Department of Fish and Wildlife (CDFW), has identified seven substrate-defined seafloor habitats in California's State Waters that can be classified using sonar data and seafloor video and photography. These habitats include rocky banks, intertidal zones, sandy or soft ocean bottoms, underwater pinnacles, kelp forests, submarine canyons, and seagrass beds. The following five depth zones, which determine changes in species composition, have been identified: Depth Zone 1, intertidal; Depth Zone 2, intertidal to 30 m; Depth Zone 3, 30 to 100 m; Depth Zone 4, 100 to 200 m; and Depth Zone 5, deeper than 200 m (California Department of Fish and Wildlife, 2008). The CDFW habitats, with the exception of depth zones, can be considered a subset of a broader classification scheme of Greene and others (1999) that has been used by the U.S. Geological Survey (USGS) (Cochrane and others, 2003, 2005). These seafloor-character maps are generalized polygon shapefiles that have attributes derived from Greene and others (2007).

A 2007 Coastal Map Development Workshop, hosted by the USGS in Menlo Park, California, identified the need for more detailed (relative to Greene and others' [1999] attributes) raster products that preserve some of the transitional character of the seafloor when substrates are mixed and (or) they change gradationally. The seafloor-character map, which delineates a subset of the CDFW habitats, is a GIS-derived raster product that can be produced in a consistent manner from data of variable quality covering large geographic regions.

The following six substrate classes are identified in the Offshore of San Francisco map area:

- Class I: Fine- to medium-grained smooth sediment
- Class II: Mixed smooth sediment and rock
- Class III: Rock and boulder, rugose
- Class IV: Medium- to coarse-grained sediment (in scour depressions)
- Class V: Anthropogenic material (smooth, hard)
- Class VI: Anthropogenic material (rugged)

The seafloor-character map of the Offshore of San Francisco map area (sheet 5) was produced using video-supervised maximum likelihood classification of the bathymetry and intensity of return from sonar systems, following the method described by Cochrane (2008). The two variants used in this classification were backscatter intensity and derivative rugosity, which is a standard calculation performed with the National Oceanic and Atmospheric Administration (NOAA) benthic-terrain modeler (available at http://coast.noaa.gov/digitalcoast/tools/btm; last accessed April 5, 2011) using a 3-pixel by 3-pixel array of bathymetry.

Classes I, II, and III values were delineated using multivariate analysis. Class IV (medium- to coarse-grained sediment, in scour depressions) values were determined on the basis of their visual characteristics using both shaded-relief bathymetry and backscatter (slight depression in the seafloor, very high backscatter return). Class IV (smooth, hard anthropogenic material) and Class V (rugged anthropogenic material) values were determined on the basis of their visual characteristics and the known location of manmade features. The resulting map (gridded at 2 m) was cleaned by hand to remove data-collection artifacts (for example, the trackline nadir).

On the seafloor-character map (sheet 5), the six substrate classes have been colored to indicate the California MLPA depth zones and the Coastal and Marine Ecological Classification Standard (CMECS) slope zones (Madden and others, 2008) in which they belong. The California MLPA depth zones are Depth Zone 1 (intertidal), Depth Zone 2 (intertidal to 30 m), Depth Zone 3 (30 to 100 m), Depth Zone 4 (100 to 200 m), and Depth Zone 5 (greater than 200 m); in the Offshore of San Francisco map area, only Depth Zones 2, 3, and 4 are present. The slope classes that represent the CMECS slope zones are Slope Class 1 = flat (0° to 5°), Slope Class 2 = sloping (5° to 30°), Slope Class 3 = steeply sloping (30° to 60°), Slope Class 4 = vertical (60° to 90°), and Slope Class 5 = overhang (greater than 90°); in the Offshore of San Francisco map area, only Slope Classes 1 and 2 are present. The final classified seafloor-character raster map image has been draped over the shaded-relief bathymetry for the area (sheets 1 and 2) to produce the image shown on the seafloor-character map on sheet 5.

The seafloor-character classification also is summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 70.5 percent (122.0 km^2) of the map area: 68.1 percent (117.8 km^2) is in Depth Zone 2, 2.3 percent (3.9 km^2) is in Depth Zone 3, and 0.1 percent (0.2 km^2) is in Depth Zone 4. Mixed smooth sediment (sand and gravel) and rock (that is, sediment typically forming a veneer over bedrock, or rock outcrops having little to no relief) make up 18.1 percent (31.3 km^2) of the map area: 11.9 percent (20.7 km^2) is in Depth Zone 2, 6.1 percent (10.5 km^2) is in Depth Zone 3, and 0.1 percent (0.2 km^2) is in Depth Zone 4. Rock and boulder, rugose (rock and boulder outcrops having high surficial complexity) make up less than 0.8 percent (1.4 km^2) of the map area: 0.5 percent (0.8 km^2) is in Depth Zone 2, 0.3 percent (0.6 km^2) is in Depth Zone 3, and less than 0.1 percent (< 0.1 km^2) is in Depth Zone 4. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than surrounding seafloor that may include active sand waves and sediment ripples) makes up 10.5 percent (18.1 km^2) of the map area: 8.1 percent (13.9 km^2) is in Depth Zone 2, 2.4 percent (4.1 km^2) is in Depth Zone 3, and less than 0.1 percent (<0.1 km^2) is in Depth Zone 4. Rugged anthropogenic material (a pipe and surrounding current scours), present only in Depth Zone 2, makes up less than 0.1 percent (<0.1 km^2) of the map area. Smooth, hard anthropogenic material (for example, debris surrounding the pipe), present only in Depth Zone 2, makes up 0.1 percent (0.2 km^2) of the map area.

A small number of video observations were used to supervise the numerical classification of the seafloor. All video observations (see sheet 6) are used for accuracy assessment of the seafloor-character map after classification. Due to the limited visibility throughout the video survey in this region, additional sediment samples were also used for ground-truthing. These samples were collected in 2010 by the USGS using a Smith McIntyre grab sampler and photographed in the field. To compare observations to classified pixels, each observation point is assigned a class (I, II, or III), according to the visually derived, major or minor geologic component (for example, sand or rock) and the abiotic complexity (vertical variability) of the substrate recorded during ground-truth surveys (table 4–1; see also, chapter 5 of this pamphlet). Class IV values were assigned on the basis of the observation of one or more of a group of features that includes both larger scale bedforms (for example, sand waves), as well as sediment-filled scour depressions that resemble the “rippled scour depressions” of Cacchione and others (1984) and Phillips and others (2007) and also the “sorted bedforms” of Murray and Thieler (2004), Goff and others (2005), and Trembanis and Hume (2011). On the geologic map (see sheet 10 of this report), they are referred to as “marine shelf scour depressions.” Class V and VI values were determined from the visual characteristics and known locations of manmade features.

Next, circular buffer areas were created around individual observation points using a 10-m radius to account for layback and positional inaccuracies inherent to the towed-camera system. The radius length is an average of the distances between the positions of sharp interfaces seen on both the video (the position of the ship at the time of observation) and sonar data, plus the distance covered during a 10-second observation period at an average speed of 1 nautical mile/hour. Each buffer, which covers more than 300 m^2, contains approximately 77 pixels. The classified (I, II, III) buffer is used as a mask to extract pixels from the seafloor-character map. These pixels are then compared to the class of the buffer. For example, if the shipboard-video observation is Class II (mixed smooth sediment and rock), but 12 of the 77 pixels within the buffer area are characterized as Class I (fine- to medium-grained smooth sediment), and 15 (of the 77) are characterized as Class III (rock and boulder, rugose), then the comparison would be “Class I, 12; Class II, 50; Class III, 15” (fig. 4–1). If the video observation of substrate is Class II, then the classification is accurate because the majority of seafloor pixels in the buffer are Class II. The accuracy values in table 4–2 represent the final of several classification iterations aimed at achieving the best accuracy, given the variable quality of sonar data (see discussion in Cochrane, 2008) and the limited ground-truth information available when compared to the continuous coverage provided by swath sonar. Presence/absence values in table 4–2 reflect the percentages of observations where the sediment classification of at least one pixel within the buffer zone agreed with the observed sediment type at a certain location.

The seafloor in the Offshore of San Francisco map area is predominantly covered by Class I sediment composed of sand and mud. There are a few exposed rugose rock outcrops (Class III) situated mostly in the nearshore areas of the Golden Gate channel. Large sand-wave fields, numerous regions of rippled sediment and mixed hard substrate dominate the channel entrance and surrounding regions.

The classification accuracy of Classes I, II, and IV (79 percent, 61 percent, and 57 percent accurate, respectively; table 4–2) is determined by comparing shipboard video observations, sediment samples, and the classified map. There was only one video observation point (representing a 1-minute segment) of Class VI sediment (crossing a pipe). This one observation point over the pipe (Class VI) was within the 10 m buffer zone (100 percent presence/absence) but resulted in overall weaker agreement (23 percent) in Class VI (pipe) due to the linear nature of the pipe. A single buffered observation locale of 77 pixels is likely to contain many other classes of pixels over a narrow linear object. There were no video observations or sediment samples retrieved from Class III (rugose rock) and Class V (smooth, hard anthropogenic material surrounding the pipe) substrate. The classification accuracy of Classes I, II, and IV are acceptable given the marginal quality of the backscatter intensity data (sheet 3) upon which the classification is partly based. Due to low visibility during the ground-truth video survey, there are an insufficient number of observations from Classes III, V, and VI to calculate classification accuracy for those classes.

Table 4–1. Conversion table showing how video observations of primary substrate (more than 50 percent seafloor coverage), secondary substrate (more than 20 percent seafloor coverage), and abiotic seafloor complexity (in first three columns) are grouped into seafloor-character-map Classes I, II, III, IV, and VI for use in supervised classification and accuracy assessment in Offshore of San Francisco map area.

[In areas of low visibility where primary and secondary substrate could not be identified with confidence, recorded observations of substrate (in fourth column) were used to assess accuracy]

Primary-substrate component	Secondary-substrate component	Abiotic seafloor complexity	Low-visibility observations
Class I			
sand	sand	low	
sand	sand	moderate	
Class II			
boulders	sand	moderate	
cobbles	cobbles	low	
gravel	sand	low	
sand	cobbles	low	
sand	gravel	low	
sand	gravel	moderate	

Primary-substrate component	Secondary-substrate component	Abiotic seafloor complexity	Low-visibility observations
sand	rock	moderate	
Class III			
rock	rock	moderate	
Class IV			
sand	sand	low	
			megaripples
			oscillatory megaripples
			depression
Class VI			
boulders	sand	moderate	

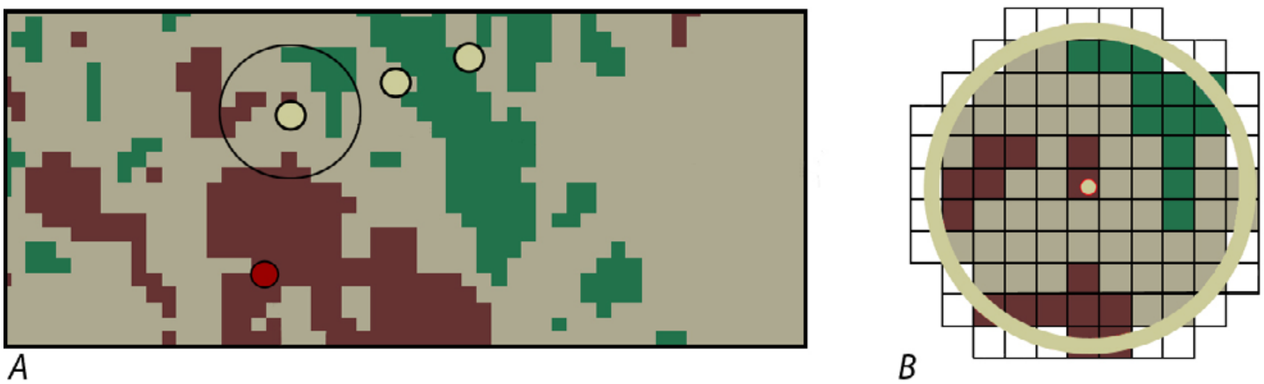

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted in *B*. *B*, Pixels of seafloor-character data within 10-m-radius buffer centered on one individual ground-truth video observation.

Table 4–2. Accuracy-assessment statistics for seafloor-character-map classifications in Offshore of San Francisco map area.

[Accuracy assessments are based on video observations and sediment samples (N/A, no accuracy assessment was conducted)]

Class	Number of observations	% majority	% presence/absence
I—Fine- to medium-grained smooth sediment	146	78.6	89.7
II—Mixed smooth sediment and rock	48	61.3	85.4
III—Rock and boulder, rugose	0	N/A	N/A
IV—Medium- to coarse-grained sediment (in scour depressions)	64	56.8	87.5
V—Smooth, hard anthropogenic feature	0	N/A	N/A
VI—Rugged anthropogenic feature	1	N/A	N/A

Chapter 5. Ground-Truth Studies for the Offshore of San Francisco Map Area (Sheet 6)

By Nadine E. Golden and Guy R. Cochrane

To validate the interpretations of sonar data in order to turn it into geologically and biologically useful information, the U.S. Geological Survey (USGS) towed a camera sled (fig. 5–1) over specific locations throughout the Offshore of San Francisco map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred on two separate cruises in 2007 and 2008. The camera sled was towed 1 to 2 m above the seafloor at speeds of between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 18.39 trackline kilometers of video and 479 still photographs, in addition to 545 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

Figure 5–1. Photograph of camera sled used in USGS 2008 ground-truth survey.

During the cruise, the USGS camera sled housed two standard-definition (640×480 pixel resolution) video cameras: one was forward looking, and the other was downward looking. During the 2008 cruise, a larger camera sled was used that housed two standard-definition (640×480 pixel resolution) video cameras (one forward looking and one downward looking), as well as a high-definition (1,080×1,920 pixel resolution) video camera and an 8-megapixel digital still camera. During this cruise, in addition to recording the seafloor characteristics, a digital still photograph was captured once every 30 seconds.

The camera-sled tracklines (shown by colored dots on the map on sheet 6) are sited in order to visually inspect areas representative of the full range of bottom hardness and rugosity in the map area. The video is fed in real time to the research vessel, where USGS and National Oceanic and Atmospheric Administration (NOAA) scientists record both the geologic and biologic character of the seafloor. While the camera is deployed, several different observations are recorded for a 10-second period once every minute, using the protocol of Anderson and others (2007). Observations of primary substrate, secondary substrate, slope, abiotic complexity, biotic complexity, and biotic cover are mandatory. Observations of key geologic features and the presence of key species also are made.

Primary and secondary substrate, by definition, constitute greater than 50 and 20 percent of the seafloor, respectively, during an observation. The grain-size values that differentiate the substrate classes are based on the Wentworth (1922) scale, and the sand, cobble, and boulder sizes are classified as in Wentworth (1922). However, the difficulty in distinguishing the finest divisions in the Wentworth (1922) scale during video observations made it necessary to aggregate some grain-size classes, as was done in the Anderson and others (2007) methodology: the granule and pebble sizes have been grouped together into a class called “gravel,” and the clay and silt sizes have been grouped together into a class called “mud.” In addition, hard bottom and clasts larger than boulder size are classified as “rock.” Benthic-habitat complexity, which is divided into abiotic (geologic) and biotic (biologic) components, refers to the visual classification of local geologic features and biota that potentially can provide refuge for both juvenile and adult forms of various species (Tissot and others, 2006).

Sheet 6 contains a smaller, simplified (depth-zone symbology has been removed) version of the seafloor-character map on sheet 5. On this simplified map, the camera-sled tracklines used to ground-truth survey the sonar data are shown by aligned colored dots, each dot representing the location of a recorded observation. A combination of abiotic attributes (primary- and secondary-substrate compositions), as well as vertical variability, were used to derive the different classes represented on the seafloor-character map (sheet 5); on the simplified map, the derived classes are represented by colored dots. Also on this map are locations of the detailed views of seafloor character, shown by boxes (Boxes A through C); for each view, the box shows the locations (indicated by colored stars) of representative seafloor photographs. For each photograph, an explanation of the observed seafloor characteristics recorded by USGS and NOAA scientists is given. Note that individual photographs often show more substrate types than are reported as the primary and secondary substrate. Organisms, when present, are labeled on the photographs.

The ground-truth survey is designed to investigate areas that represent the full spectrum of high-resolution multibeam bathymetry and backscatter-intensity variation. Figure 5–2 shows that, the majority of useful seafloor observations were obtained in areas with sand-dominated sedimentary deposits, and that the Offshore San Francisco map area is dominated by sand sedimentary bottom but there is some rocky habitat. Rocky habitat in the nearshore and within the Bay is undersampled. Robust models of the distribution of flora and fauna in the map area will require additional video-surveying effort.

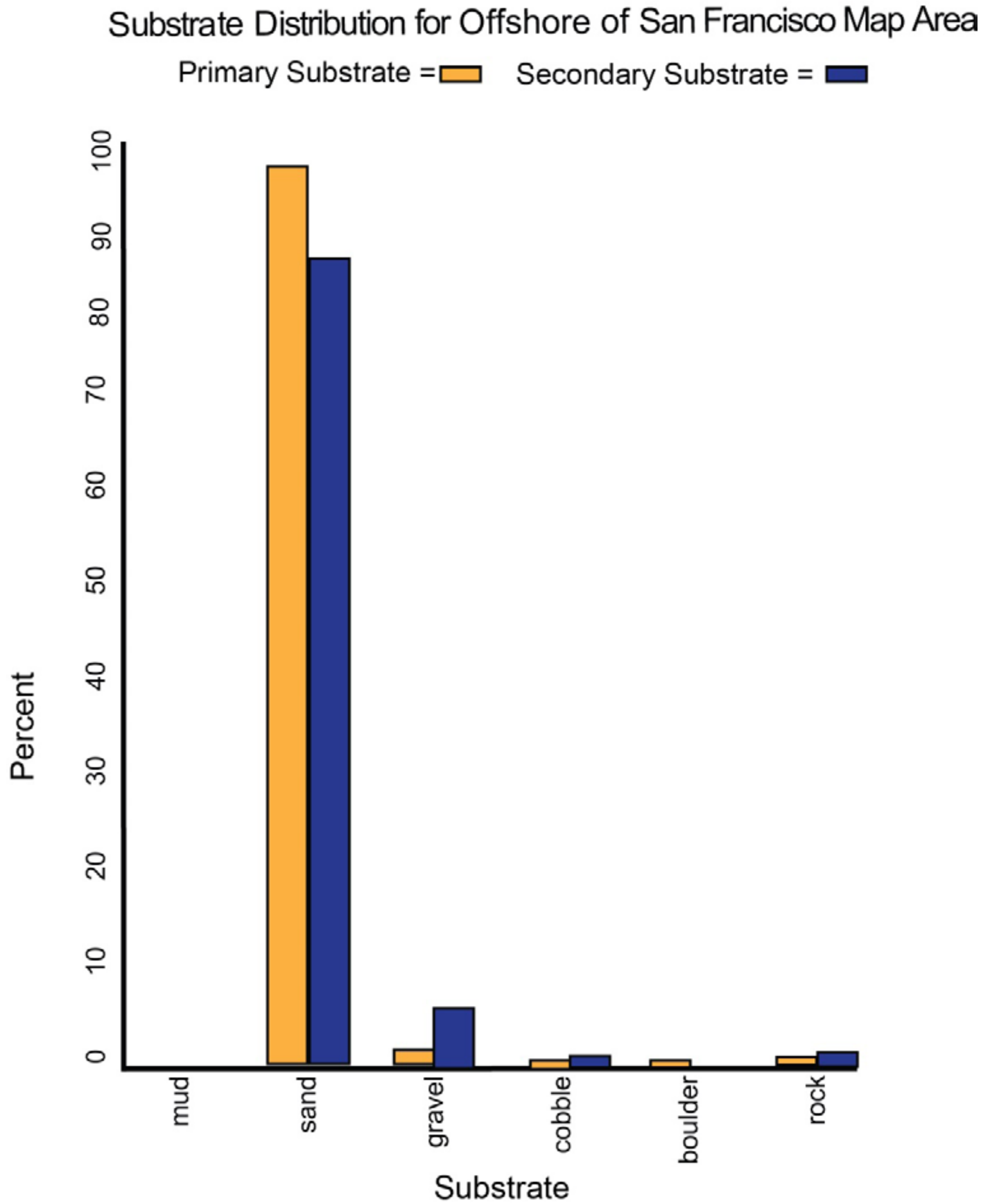

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of San Francisco map area.

Chapter 6. Potential Marine Benthic Habitats Map of the Offshore of San Francisco Map Area (Sheet 7)

By H. Gary Greene and Charles A. Endris

The map on sheet 7 shows “potential” marine benthic habitats in the Offshore of San Francisco map area, representing a substrate type, geomorphology, seafloor process, or any other attribute that may provide a habitat for a specific species or assemblage of organisms. This map, which is based largely on seafloor geology, also integrates information displayed on several other thematic maps of the Offshore of San Francisco map area. High-resolution sonar bathymetry data, converted to depth grids (seafloor DEMs; sheet 1), are essential to development of the potential marine benthic habitat map, as is shaded-relief imagery (sheet 2), which allows visualization of seafloor terrain and provides a foundation for interpretation of submarine landforms.

Backscatter maps (sheet 3) also are essential for developing potential benthic habitat maps. High backscatter is further indication of “hard” bottom, consistent with interpretation as rock or coarse sediment. Low backscatter, indicative of a “soft” bottom, generally indicates a fine-sediment environment. Habitat interpretations also are informed by actual seafloor observations from ground-truth surveying (sheet 6), by seafloor-character maps that are based on video-supervised maximum-likelihood classification (sheet 5), and by seafloor-geology maps (sheet 10). The habitat interpretations on sheet 7 are further informed by the usSEABED bottom-sampling compilation of Reid and others (2006).

Broad, generally smooth areas of seafloor that lack sharp and angular edge characteristics are mapped as “sediment;” these areas may be further defined by various sedimentary features (for example, erosional scours and depressions) and (or) depositional features (for example, dunes, mounds, or sand waves). In contrast, many areas of seafloor bedrock exposures are identified by their common sharp edges and high relative relief; these may be contiguous outcrops, isolated parts of outcrop protruding through sediment cover (pinnacles or knobs), or isolated boulders. In many locations, areas within or around a rocky feature appear to be covered by a thin veneer of sediment; these areas are identified on the habitat map as “mixed” induration (that is, containing both rock and sediment). The combination of remotely observed data (for example, high-resolution bathymetry and backscatter, seismic-reflection profiles) and directly observed data (for example, camera transects, sediment samples) translates to higher confidence in the ability to interpret broad areas of the seafloor.

To avoid any possible misunderstanding of the term “habitat,” the term “potential habitat” (as defined by Greene and others, 2005) is used herein to describe a set of distinct seafloor conditions that in the future may qualify as an “actual habitat.” Once habitat associations of a species are determined, they can be used to create maps that depict actual habitats, which then need to be confirmed by in situ observations, video, and (or) photographic documentation.

Classifying Potential Marine Benthic Habitats

Potential marine benthic habitats in the Offshore of San Francisco map area are mapped using the Benthic Marine Potential Habitat Classification Scheme, a mapping-attribute code developed by Greene and others (1999, 2007). This code, which has been used previously in other offshore California areas (see, for example, Greene and others, 2005, 2007), was developed to easily create categories of marine benthic habitats that can then be queried within a GIS or a database. The code contains several categories that can be subdivided relative to the spatial scale of the data. The following categories can be applied directly to habitat interpretations determined from remote-sensing imagery collected at a scale of tens of kilometers to one meter: Megahabitat, Seafloor Induration, Meso/Macrohabitat, Modifier, Seafloor Slope, Seafloor Complexity, and Geologic Unit. Additional categories of Macro/Microhabitat, Seafloor Slope, Seafloor Complexity, and Geologic Attribute can be applied to habitat interpretations determined from seafloor samples, video, still photographs, or direct observations at a scale of 10 meters to a few centimeters. These two scale-dependent groups of categories can be used together, to define a habitat across spatial scales, or separately, to compare large- and small-scale habitat types.

The four categories and their attribute codes that are used on the Offshore of San Francisco map are explained in detail below (note, however, that not all categories may be used in a particular map area, given the study objectives, data availability, or data quality); attribute codes in each category are depicted on the map by the letters and, in some cases, numbers that make up the map-unit symbols:

Megahabitat—Based on depth and general physiographic boundaries; used to distinguish features on a scale of tens of kilometers to kilometers. Depicted on map by capital letter, listed first in map-unit symbol; generalized depth ranges are given below.

E = Estuary (0 to 100 m)
S = Shelf; continental and island shelves (0 to 200 m)

Seafloor Induration—Refers to substrate hardness. Depicted on map by lower-case letter, listed second in map-unit symbol; may be further subdivided into distinct sediment types, depicted by lower-case letter(s) in parentheses, listed immediately after substrate hardness; multiple attributes listed in general order of relative abundance, separated by slash; queried where inferred.

h = Hard bottom (for example, rock outcrop or sediment pavement)
m = Mixed hard and soft bottom (for example, local sediment cover of bedrock)
s = Soft bottom; sediment cover
(b) = Boulders
(g) = Gravel
(s) = Sand
(m) = Mud, silt, and (or) clay

Meso/Macrohabitat—Related to scale of habitat; consists of seafloor features one kilometer to one meter in size. Depicted on map by lower-case letter and, in some cases, additional lower-case letter in parentheses, listed third in map-unit symbol; multiple attributes separated by slash.

(b)/p = Pinnacle indistinguishable from boulder
d = Deformed, tilted and (or) folded bedrock; overhang
e = Exposure; bedrock
g = Gully; channel
h = Hole; depression
m = Mound; linear ridge
p = Pinnacle; cone
s = Scarp, cliff, fault, or slump scar
w = Dynamic bedform

Modifier—Describes texture, bedforms, biology, or lithology of seafloor. Depicted on map by lower-case letter, in some cases followed by additional lower-case letter(s) either after a hyphen or in parentheses (or both), following an underscore; multiple attributes separated by slash.

_a = Anthropogenic (artificial reef, breakwall, shipwreck, disturbance)
- _a-dd = Dredge disturbance
- _a-dg = Dredge groove or channel
- _a-dm = Dredge mound (disposal)
- _a-dp = Dredge pothole
- _a-f = Ferry (or other vessel) propeller-wash scour or scar
- _a-g = Groin, jetty, rip-rap
- _a-p = Pipeline
- _a-td = Trawl disturbance

_b = Bimodal (conglomeratic, mixed [gravel, cobbles, and pebbles])
_c = Consolidated sediment (claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
_d = Differentially eroded
_f = Fracture, joint; faulted
_g = Granite
_h = Hummocky, irregular relief
_r = Ripple (amplitude, greater than 10 cm)
_s = Scour (current or ice; direction noted)
_u = Unconsolidated sediment

Examples of Attribute Coding

To illustrate how these attribute codes can be used to describe remotely sensed data, the following examples are given:

Ss(s)_u = Soft, unconsolidated sediment (sand), on continental shelf.
Es(s/m)_r/u = Rippled, soft, unconsolidated sediment (sand and mud), in estuary.
She_g = Hard rock outcrop (granite), on continental shelf.

Map Area Habitats

The Offshore of San Francisco map area includes the San Francisco Bay estuary and the offshore inner continental shelf. Delineated in the map area are 50 potential marine benthic habitat types: 19 are found on the continental shelf (“Shelf” megahabitat), and 31 are identified in San Francisco Bay estuary (“Estuary” megahabitat).

The meso- and macrohabitats on the continental shelf include soft unconsolidated sediment (7 habitat types) such as sand and gravel, a large sediment (sand) bar (the horseshoe-shaped bar offshore of the Golden Gate), and dynamic features such as mobile sand sheets, sediment waves, and rippled sediment depressions; mixed substrate (3 habitat types) such as soft sand and gravels overlying consolidated sedimentary bedrock and gravel pavement; hard substrate (3 habitat types) such as deformed and differentially eroded bedrock, pinnacles and boulders; anthropogenic features (6 habitat types) such as dredge spoil fields, dredged channels, and pipelines with hard rock ballast.

The meso- and macrohabitats in San Francisco Bay include soft unconsolidated sediment (15 habitat types) such as sediment waves, rippled sand, gravel and mud; mixed substrate of soft unconsolidated sediment covering hard rock (2 habitat types); hard substrate (3 habitat types) such as deformed consolidated bedrock, pinnacles and boulders; and anthropogenic features (11 habitat types) such as dredged areas, sand and gravel mining, and dynamited rocks for navigation purposes.

Backscatter data show that most of the area is underlain by “soft” materials, consistent with the interpretation that unconsolidated sediments dominate habitat in the mapped area. Sedimentary processes are quite active and, thus, habitats are highly dynamic. In addition, erosion through shelf sediments down to a coarser lag has produced sediment-filled scour depressions that resemble “ripple-scour depressions” of Cacchione and others (1984) and Phillips and others (2007), which are found mainly on the shelf, and deep scour depressions that are found in the central part of San Francisco Bay.

Of the 173.45 km^2 in the map area, 146.66 km^2 (84.6 percent) was mapped on the continental shelf and 26.79 km^2 (15.4 percent) was mapped in the estuary. Soft, unconsolidated sediment is the dominant habitat type covering 159.94 km^2, representing 92.2 percent of the mapped area. Hard rock covers 5.78 km^2 (3.3 percent), while 1.76 km^2 (1 percent) is of the mixed hard-soft induration class. Anthropogenic features inside and outside the bay make up 5.97 km^2 (3.4 percent of the total mapped area).

Chapter 7. Subsurface Geology and Structure of the Offshore of San Francisco Map Area and the Bolinas to Pescadero Region (Sheets 8 and 9)

By Samuel Y. Johnson, Stephen R. Hartwell, Ray W. Sliter, Janet T. Watt, and Stephanie L. Ross

The seismic-reflection profiles presented on sheet 8 provide a third dimension, depth, to complement the surficial seafloor-mapping data already presented (sheets 1 through 7) for the Offshore of San Francisco map area. These data, which are collected at several resolutions, extend to varying depths in the subsurface, depending on the purpose and mode of data acquisition. The seismic-reflection profiles (sheet 8) provide information on sediment character, distribution, and thickness, as well as potential geologic hazards, including active faults, areas prone to strong ground motion, and tsunamigenic slope failures. The information on faults provides essential input to national and state earthquake-hazard maps and assessments (for example, Petersen and others, 2008).

The maps on sheet 9 show the following interpretations, which are based on the seismic-reflection profiles on sheet 8: the thickness of the uppermost sediment unit; the depth to base of this uppermost unit; and both the local and regional distribution of faults and earthquake epicenters (data from U.S. Geological Survey and California Geological Survey, 2010; Northern California Earthquake Data Center, 2014).

Data Acquisition

Most profiles displayed on sheet 8 (figs. 1, 2, 3, 6, 8, and 9) were collected in 2006 on USGS cruise L–1–06–NC. Data for the seismic profiles shown in figures 10 and 11 were collected in 2010 on USGS cruise S–16–10–NC. Both cruises used the SIG minisparker system, and the L–1–06–NC survey also collected some profiles using the EdgeTech 512 chirp system. The SIG minisparker system used a 500-J, high-voltage electrical discharge fired at 1 to 4 times per second, which, at normal survey speed of 4 to 4.5 nautical miles/hour, gives a data trace every 0.5 to 2.0 meters of lateral distance covered. The data were digitally recorded in standard SEG-Y 32-bit floating-point format, using Triton Subbottom Logger (SBL) software that merges seismic-reflection data with differential GPS-navigation data. After the survey, a short-window (20 ms) automatic gain control algorithm was applied to the data, along with a 160- to 1,200-Hz bandpass filter and a heave correction that uses an automatic seafloor-detection window (averaged over 30 m of lateral distance covered). The EdgeTech 512 chirp subbottom-profiling system consists of a source transducer and an array of receiving hydrophones housed in a 500-lb fish towed at a depth of several meters below the sea surface. The swept-frequency chirp source signal was 500 to 4,500 Hz and 50 ms in length, and it was recorded by hydrophones located on the bottom of the fish.

Data for figures 4, 5, and 7 on sheet 8 were collected in 1995 on USGS cruise G–2–95–SF (Childs and others, 2000; Bruns and others, 2002). Two 0.65-L air guns fired at 12.5-m intervals provided the seismic source, and data were digitally recorded on a 24-channel, 150-m-long streamer merged with GPS navigation data. Data-processing steps included deconvolution, automatic gain control, filtering at 50 to 160 Hz, stacking, and migration (Yilmaz, 1987).

Geologic Structure and Recent Deformation

The Offshore of San Francisco map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active northwest-striking faults that cumulatively form a distributed shear zone, including the San Andreas Fault, the eastern strand of the

San Gregorio Fault Zone, the Golden Gate Fault, and the Potato Patch Faults (see sheets 9, 10; Jachens and Zoback, 1999; Zoback and others, 1999; Bruns and others, 2002; Parsons and others, 2005; Ryan and others, 2008). These faults are identified on seismic-reflection data and mapped based on abrupt truncation or warping of reflections and (or) juxtaposition of reflection panels with different seismic parameters such as reflection amplitude, frequency, geometry, continuity, and vertical sequence.

The San Andreas Fault (figs. 2, 3, 5, 7, 9, 10, 11 on sheet 8), which is the dominant plate-boundary structure, extends northwest and offshore through the map area (Map E on sheet 9). The fault extends onland from the offshore 3 km south of the map area at Mussel Rock, and 10 kilometers north of the map area at Bolinas Lagoon. The San Andreas Fault in this map area has an estimated slip rate of 17 to 24 mm/yr (U.S. Geological Survey and California Geological Survey, 2010).

The San Gregorio Fault Zone, another major strike-slip fault system within the transform plate boundary, extends predominantly in the offshore for about 400 km along the central California coast. Cumulative lateral slip in this region is estimated to be about 4 to 10 mm/yr (U.S. Geological Survey and California Geological Survey, 2010) near San Francisco, divided between an eastern strand (figs. 2, 5, 9 on sheet 8) that converges with the San Andreas Fault in the map area and similarly goes onshore near Bolinas, and a western strand that lies west of the map area and may merge with the northwest-trending, northeast-dipping Point Reyes Fault (Map E on sheet 9; Bruns and others, 2002; Ryan and others, 2008). The Potato Patch Fault (figs. 2, 5, 7, 9 on sheet 8) lies obliquely between the San Andreas and the eastern strand of the San Gregorio Fault Zone between Pacifica and Bolinas and converges northward with the San Andreas Fault (see sheet 9) within the map area. The Golden Gate Fault (figs. 1, 3, 4, 5, 7, 9, 10 on sheet 8) parallels and lies east of the San Andreas Fault between San Francisco and Bolinas.

Zoback and others (1999) and Ryan and others (2008) noted a northward bend in the trend (from 325° to 330°) of both the San Andreas and San Gregorio Faults offshore San Francisco, resulting in a change from local contractional to extensional deformation. The inferred extensional setting is consistent with subsidence of the San Francisco ebb-tidal delta and with development of the prominent San Andreas graben (figs. 1, 3 on sheet 8; fig. 1 on sheet 9; Cooper, 1973; Bruns and others, 2002; Ryan and others, 2008). This graben (about 7 km long and 2.5 km wide) is bounded to the west by the San Gregorio Fault Zone (eastern strand) and Bolinas shelf, and to the east by the Golden Gate Fault and the Marin shelf. The basin floor tilts gently westward from the Golden Gate Fault to the San Andreas Fault, along which the basin fill is thickest. The abrupt northern basin margin could have formed either (1) as an extensional normal fault, or (2) as a northwest "restraining bend" in the Golden Gate Fault as its trace converges northward with the San Andreas Fault. The southern basin margin appears more gradual and lies offshore of San Francisco within a sea-level lowstand paleovalley (see below).

Map E on Sheet 9 shows the regional pattern of major faults and earthquakes. Fault location is simplified and compiled from our mapping within California's State Waters (for example, sheet 10) and from the U.S. Geological Survey and California Geological Survey Quaternary fault and fold database (2010). Earthquake epicenters are from the Northern California Earthquake Data Center (2014), maintained by the USGS and the University of California, Berkeley, Seismological Laboratory; all events of magnitude 2.0 and greater for the time period 1967 through March 2014 are shown. The largest concentration of earthquakes in the map area clearly occurs within the broad San Andreas Fault Zone between Pacifica and Bolinas; events west of the eastern strand of the San Gregorio Fault Zone and east of the Golden Gate Fault are much less common. Map E also shows the inferred location of the devastating great 1906 California earthquake (M7.8, 4/18/1906), thought to have nucleated on the San Andreas Fault offshore of San Francisco (for example, Bolt, 1968; Lomax, 2005).

Seismic-Reflection Imaging of the San Francisco Ebb-Tidal Delta, Golden Gate Channel, and Adjacent Continental Shelf

Map sheet 8 shows seismic-reflection profiles in the Offshore of San Francisco map area, which includes the deep channel and sand-wave field west of the Golden Gate (see sheets 1, 2), the San Francisco ebb-tidal delta (including the "San Francisco Bar"), and portions of the Marin shelf to the north and Pacifica-Pescadero shelf to the south. The offshore delta and adjacent shelf are smooth, relatively flat (less than 0.25°) and shallow (less than 20 m). The sand-wave field covers an area of approximately 4 km^2 in water depths ranging from 30 to 106 m (Barnard and others, 2006a,b).

These areas are variably underlain by uppermost Pleistocene and Holocene sediment deposited in the last about 21,000 years during the sea-level rise that followed the Last Glacial Maximum (LGM) and the last major lowstand. Sea level was about 125 m lower during the LGM, at which time the shoreline was more than 45 km west of San Francisco near the Farallon Islands. The Offshore of San Francisco map area was emergent during the LGM lowstand and formed part of a large alluvial plain connected to a drainage basin that included much of California's Central Valley (Atwater and others, 1977). The river system flowed westward through the present narrows at the Golden Gate, constrained to an alluvial valley that was bounded on the north and south by bedrock highlands including what is now the Pacifica-Pescadero and Bolinas shelves (see below). The post-LGM rise in sea level was rapid, about 9 to 11 meters per thousand years, until about 7,000 years ago when it slowed considerably to about 1 meter per thousand years (Peltier and Fairbanks, 2006). Rising seas are thought to have entered the Golden Gate about 11,000 to 10,000 years ago with subsequent marine flooding leading to progressive growth of San Francisco Bay (Atwater and others, 1977). The axis of the lowstand fluvial system is represented on Maps A and B (sheet 9) by the obvious west-southwest trending, linear zone of sediment thickness and increased depth-to-base of sediment. Within California's State Waters, the San Francisco ebb-tidal delta is now largely confined to this lowstand paleovalley.

The sediments deposited during the post-LGM sea-level rise in the paleovalley and on the adjacent shelf areas are shaded blue in the high-resolution seismic-reflection profiles on Sheet 8 and their thickness is shown on Sheet 9 (Maps B, D). These strata are typically characterized either by "acoustic transparency" or by parallel, low amplitude, low to high frequency, continuous to moderately continuous, diffuse reflections (terminology from Mitchum and others, 1977). The acoustic transparency (that is, lack of internal reflections) can be caused by wave winnowing, resulting in uniform sediment grain size and hence, a lack of acoustic impedance contrasts needed to produce seismic reflections. The contact between these sediments and underlying strata is a transgressive surface of erosion commonly marked by angularity, channeling, or a distinct upward change to lower-amplitude, more diffuse reflections. It is emphasized that the base of this unit is an interpretation somewhat hindered by acoustic transparency and by "acoustic masking," which is associated with the presence of interstitial gas within the sediment (Fader, 1997; Ryan and others, 2008).

In the Golden Gate channel, strong tidal currents, typically exceeding 2.5 m/sec, are associated with an enormous tidal prism of about 2 billion m^3 (Barnard and others, 2006a,b). Acceleration of these currents has scoured a bedrock channel (see sheets 1, 2, 10) that has a maximum depth of 113 m. Large fields of sand waves have formed both east and west of this channel in locations where flow expands and current decelerates (see sheets 1, 2, 3, 4). Seismic-reflection profiles that image the scour channel and sand-wave field (figs. 6, 8 on sheet 8) reveal the surface morphology of these large bedforms (note vertical exaggeration) and internal east-dipping crossbeds in the eastern part of the field.

Thickness and Depth to Base of Uppermost Pleistocene and Holocene Deposits

Maps on sheet 9 show the thickness and the depth to base of uppermost Pleistocene and Holocene (post-LGM) deposits, both for the Offshore of San Francisco map area (Maps A, B) and, to establish regional context, for a larger area (about 91 km of coast) that extends from the Bolinas area to Pescadero (Maps C, D). To make these maps, water bottom and depth to base of the LGM horizons were mapped from seismic-reflection profiles using Seisworks software. The difference between the two horizons was exported from Seisworks for every shot point as XY coordinates (UTM zone 10) and two-way travel time (TWT). The thickness of the post–LGM unit (Maps B, D) was determined by applying a sound velocity of 1,600 m/sec to the TWT, resulting in thicknesses as great as about 57 m. The thickness points were interpolated to a preliminary continuous surface, overlaid with zero-thickness bedrock outcrops (sheet 10), and contoured following the methodology of Wong and others (2012). Data within Golden Gate channel and San Francisco Bay were excluded from the contouring because the seismic-reflection data commonly don't provide internal reflections through the coarse sediment that comprises the sand waves, and because our trackline coverage was too sparse to adequately image the highly variable changes in sediment thickness that likely characterize these areas.

Several factors required manual editing of the preliminary thickness maps to make the final products. The San Andreas, San Gregorio, Golden Gate, and Potato Patch Faults disrupt the sediment sequence in the region (Maps D, E on sheet 9). The thickness data points also are dense along tracklines (about 1 m apart) and sparse between tracklines (1 km apart), resulting in contouring artifacts. To incorporate the effect of the faults, to remove irregularities from interpolation, and to reflect other geologic information and complexity, the resulting interpolated contours were modified. Contour modifications and regridding were repeated several times to produce the regional sediment-thickness maps (Maps B, D). Information for the depth to base of the post-LGM unit (Maps A, C) was generated by adding the thickness data to water depths determined by multibeam bathymetry (see sheet 1).

The thickness of the post-LGM unit in the Offshore of San Francisco map area ranges from 0 to 57 m (Map B on sheet 9), and the depth to the base of this unit ranges from less than 15 to 78 m (Map A on sheet 9). Mean sediment thickness for the map area is 16.5 m, and the total sediment volume is 1.7 x 10^9 m^3 (table 7–1). The most rapid changes in thickness occur along the Golden Gate and San Andreas Faults, on the eastern margin of and within the San Andreas graben. Sediment within this rapidly subsiding basin has a mean thickness of 35.2 m in the map area, while sediment on the adjacent Marin shelf to the east has a mean sediment thickness of 11.8 m. Although the lowstand paleovalley and the southern part of the San Andreas graben are superimposed, the northern flank of the paleovalley is here used as the "domain" boundary (see below) in calculating sediment thicknesses and volumes. Post-LGM sediment in the San Francisco paleovalley has a mean thickness of 19.5 m, with a maximum thickness of 32 m along its axis. The portion of the Pacifica-Pescadero shelf that lies south of the paleovalley and within the map area has a mean sediment thickness of 7.4 m.

The San Andreas graben and San Francisco paleovalley comprise 15 and 34 percent of the map area but contain 31 and 40 percent of its sediment volume, respectively. In contrast, the Marin shelf and Pacifica-Pescadero shelf comprise 22 and 29 percent of the map area and contain 16 and 13 percent of its sediment volume, respectively. The contrast between the sediment-rich and sediment-poor domains reflects the presence or absence of "sediment accommodation space" (for example, Catuneanu, 2006). Accommodation space is provided in the San Andreas graben by rapid subsidence and in the San Francisco paleovalley by lowstand fluvial erosion. In contrast, the adjacent Marin and Pacifica-Pescadero shelves are elevated areas characterized by significant sediment bypass. The high wave energy characteristic of the region (Barnard and others, 2007) efficiently reworks sediment and transports it off the inner shelf to deeper water.

Five different "domains" of sediment thickness are recognized on the regional sediment-thickness map (Map D on sheet 9): (1) the Bolinas shelf, located west of the east strand of the San Gregorio Fault Zone, in the northwestern part of the regional map (Map D); (2) the San Andreas graben, located between the San Gregorio Fault Zone and the Golden Gate Fault, east-southeast of the Bolinas shelf and both southwest and southeast of the Marin shelf; (3) the Marin shelf, located both northeast and northwest of the San Andreas graben and north of the San Francisco ebb-tidal delta paleovalley; (4) the northeast-trending San Francisco ebb-tidal delta paleovalley, located outside the Golden Gate at the mouth of San Francisco Bay, between the Marin shelf and San Andreas graben on the north and the Pacifica-Pescadero shelf on the south; and (5) the Pacifica-Pescadero shelf, which is located south of the San Francisco ebb-tidal delta paleovalley and which extends south all the way to Pescadero Point (including all of the Offshore of Half Moon Bay map area).

The five sediment-thickness domains have distinct geologic controls. The Bolinas and Pacifica-Pescadero shelves are uplifting and are relatively sediment poor (mean sediment thicknesses of 0.8 and 3.6 m, respectively; table 7–1). Thicker sediment accumulations (as much as 20 m) on the western margins of the Pacifica-Pescadero shelf (within California's State Waters) are associated with west-side-down slip on the west strand of the San Gregorio Fault Zone and with deposition on the outboard, west-dipping Pigeon Point block (McCulloch, 1987) (fig. 2 on sheet 9) farther south offshore of Pescadero Point. The San Andreas graben is a rapidly subsiding, fault-controlled sedimentary basin that has sediment thicknesses of as much as 57 m; the Marin shelf forms the uplifted northeastern and northwestern margins of this basin. The San Francisco ebb-tidal delta is filling a paleovalley that formed during the last sea-level lowstand, with sediment thicknesses of as much as 32 m along the trough axis. Although the southern part of the San Andreas graben may extend into the paleovalley, the north flank of the paleovalley is used here as the boundary when calculating sediment volumes for the five sediment-thickness domains (table 7–1). Subsidence in the San Francisco ebb-tidal delta paleovalley and the San Andreas graben can be partly attributed to the northward change in strike of both the San Andreas and San Gregorio Fault Zones offshore of San Francisco, which has resulted in the local change from contractional deformation to extensional deformation (Zoback and others, 1999).

The Bolinas shelf and the San Andreas graben represent the extremes of sediment distribution in the Bolinas to Pescadero region (Maps C, D). The San Andreas graben occupies just 5.1 percent of the region but contains about 27.6 percent of its sediment. In contrast, the Bolinas shelf occupies 13.6 percent of the region but contains just 1.8 percent of its sediment. The Pacifica-Pescadero shelf is relatively sediment poor, making up 66.3 percent of the region but containing 39.0 percent of its sediment.

Table 7–1. Area, sediment-thickness, and sediment-volume data for California's State Waters in Bolinas to Pescadero region (domains 1–5), as well as in Offshore of San Francisco map area.

Regional sediment-thickness domains in Bolinas to Pescadero region			
	Area (km^2)	Mean sediment thickness (m)	Sediment volume (10^6 m^3)
Entire Bolinas to Pescadero region	529	6.2	3,286
(1) Bolinas shelf, west of east strand of San Gregorio Fault Zone	72	0.8	59
(2) San Andreas graben, between San Gregorio Fault Zone and Golden Gate Fault	27	33.5	906
(3) Marin shelf, northeast and northwest of San Andreas graben, north of San Francisco ebb-tidal delta paleovalley	44	8.1	355
(4) San Francisco ebb-tidal delta paleovalley	35	19.5	685
(5) Pacifica-Pescadero shelf	351	3.6	1,281
Sediment thickness in Offshore of San Francisco map area			
Offshore of San Francisco map area	102	16.5	1,693
San Andreas graben	15	35.2	521
Marin shelf, east of San Andreas graben, north of San Francisco paleovalley	22	11.8	263
San Francisco ebb-tidal delta paleovalley	35	19.5	685
Pacifica-Pescadero shelf, south of San Francisco paleovalley	30	7.4	222

Chapter 8. Geologic and Geomorphic Map of the Offshore of San Francisco Map Area (Sheet 10)

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Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of San Francisco map area from approximate Mean High Water (MHW) to the 3-nautical-mile limit of California's State Waters. MHW is defined at an elevation of 1.46 m above the North American Vertical Datum of 1988 (NAVD 88) (Weber and others, 2005). Offshore geologic units were delineated on the basis of integrated analyses of adjacent onshore geology with multibeam bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

Onshore geology was compiled from Bonilla (1961, 1998), Knudsen and others (1997), Brabb and others, (1998), Blake and others (2000), and Witter and others (2006). Unit ages, which are derived from these sources, reflect local stratigraphic relations.

The Offshore of San Francisco map area includes the Golden Gate channel, which connects the Pacific Ocean and San Francisco Bay. San Francisco Bay, the largest estuary on the U.S. west coast, is located at the mouth of the Sacramento and San Joaquin rivers and drains over 40 percent of the state of California. The large surface area of the bay and diurnal tidal range of 1.78 m creates an enormous tidal prism (about 2 billion m^3) and strong tidal currents, commonly exceeding 2.5 m/s (Barnard and others, 2006a,b, 2007). Acceleration of these currents through the constricted inlet has led to scouring of a bedrock channel that has a maximum depth of 113 m. Large fields of sand waves (Barnard and others, 2007) (unit Qmsw) have formed both west and east of this channel as flow expands and tidal currents decelerate (sheets 1, 2, 3, 4). Active tidally influenced map units inside San Francisco Bay also include sand-dominated deposits (unit Qbd) and more coarse-grained sand, gravel, and pebble deposits (unit Qbdc).

Sand wave fields resulting from tidal flow are also present in the nearshore along the Pacific Coast, both north and south of the Golden Gate channel. The sand wave fields appear to be variably mobilized by both ebb and flood tides, but the presence of a large (about 150 km^2) ebb-tidal delta at the mouth of the bay west of the inlet indicates that net sediment transport has been to the west. The ebb-tidal delta west of the Golden Gate channel is mapped as two units. The inner part of the delta (unit Qmst) comprises a semicircular, inward-sloping (toward the Golden Gate channel), sandy seafloor at water depths of about 12 to 24 m. This inner delta has a notably smooth surface, indicating sediment transport and deposition under different flow regimes (defined by tidal current strength and depth) than those in which the sand waves formed and are maintained.

Further deceleration of tidal currents beyond the inner delta has led to development of a large, shoaling (about 8 to 12 m water depth), horseshoe shaped, delta-mouth bar (unit Qmsb). This feature (the "San Francisco Bar") surrounds the inner delta, and its central crest is cut by a dredged shipping channel that separates the northern and southern parts of the bar, the "North Bar" and "South Bar," respectively. The San Francisco Bar is shaped by both tidal currents and waves, which regularly exceed 6 m in height on the continental shelf during major winter storms (Barnard and others, 2007). This mix of tidal and wave influence results in a variably hummocky, mottled, and rilled seafloor, and this surface texture is used as a primary criteria for mapping the unit and defining its boundaries.

From outside the San Francisco Bar to the limits of the map area, the notably flat shelf (slope less than 0.2°) and the nearshore are wave-dominated and characterized by sandy marine sediment (unit

Qms). Local zones of wave-winnowed (?) coarser sediment (unit Qmsc) indicated by high backscatter (see sheet 3) occur along the coast offshore Ocean Beach. Unit Qmsc is also mapped inside and at the mouth of the Golden Gate channel where it presumably results from winnowing by strong tidal currents.

Coarser sediment also occurs as winnowed lags in rippled scour depressions (unit Qmss), recognized on the basis of high-resolution bathymetry (see sheets 1, 2) and backscatter (see sheet 3). These depressions are typically a few tens of centimeters deep and are bounded by mobile sand sheets (for example, Cacchione and others, 1984). This unit occurs primarily in the nearshore south of the Golden Gate channel offshore of Ocean Beach (water depth less than 13 m) and north of the inlet offshore Muir Beach (water depth less than 17 m).

Artificial seafloor (unit as) has several distinct map occurrences: (1) sites of active sand mining inside San Francisco Bay; (2) the dredged shipping channel at the central crest of the San Francisco Bar; (3) the sewage outfall pipe, associated rip rap, and surrounding scour channel offshore Ocean Beach; and (4) the location of a former waste disposal site about 2.5 km offshore Point Lobos.

Although the map shows the areas in which several active sedimentary units (Qmsw, Qmst, Qmsb, Qms, Qmsc, Qmss, Qbsm, Qbsc) presently occur, it is important to note that map units and contacts are dynamic and ephemeral, likely to change during large storms, and on seasonal to decadal scales based on changing external forces such as weather, climate, sea level, and sediment supply. Dallas and Barnard (2011) have noted, for example, that the ebb-tidal delta has dramatically shrunk since 1873 when the first bathymetric survey of the area was undertaken. They document an approximate 1 km landward migration of the crest of the San Francisco Bar, which they attribute to a reduction in the tidal prism of San Francisco Bay and a decrease in coastal sediment. The relative proportions of all offshore map units are shown in table 8–1.

The offshore of San Francisco map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active northwest-striking faults that cumulatively form a distributed shear zone, including the San Andreas Fault, the eastern strand of the San Gregorio Fault Zone, the Golden Gate Fault, and the Potato Patch Fault (sheets 8, 9; Bruns and others, 2002; Ryan and others, 2008). These faults are covered by Holocene sediments (mostly units Qms, Qmsb, Qmst) with no seafloor expression, and are mapped using seismic-reflection data (see sheet 8). The San Andreas Fault is the primary plate-boundary structure and extends northwest across the map area; it intersects the shoreline 10 km north of the map area at Bolinas Lagoon, and 3 km south of the map area at Mussel Rock. The San Andreas Fault in this area has an estimated slip rate of 17 to 24 mm/yr (U.S. Geological Survey and California Geological Survey, 2010), and the devastating great 1906 California earthquake (M7.8, 4/18/1906) is thought to have nucleated on the San Andreas a few kilometers offshore of San Francisco within the map area (see sheet 9; Bolt, 1968; Lomax, 2005).

The San Andreas Fault forms the boundary between two distinct basement terranes, Upper Jurassic and Lower Cretaceous rocks of the Franciscan Complex to the east, and Late Cretaceous granitic and older metamorphic rocks of the Salinian block to the west. Franciscan Complex rocks (unit KJf, undivided) form seafloor outcrops at and north of Point Lobos adjacent to onland exposures. The Franciscan is divided into 13 different units for the onshore portion of this geologic map based on different lithologies and ages, but the unit cannot be similarly divided in the offshore because of a lack of direct observation and (or) sampling. In the southern part of the map area, the San Andreas Fault also forms the southwestern boundary of the offshore occurrence of the Pliocene and Pleistocene Merced Formation (unit QTm).

Table 8–1. Areas and relative proportions of offshore geologic map units Offshore of San Francisco map area.

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine sedimentary units			
af	6,026,072	6.03	3.30
Qms	65,016,989	65.02	35.55
Qmsc	1,661,363	1.66	0.91
Qmss	192,480	0.19	0.11
Qsw	30,307,917	30.31	16.57
Qmsb	25,437,900	25.44	13.91
Qmst	34,016,197	34.02	18.60
Qbd	5,700,799	5.70	3.12
Qbdc	3,551,854	3.55	1.94
Total, sedimentary units	171,911,572	171.91	94.00
Marine bedrock and (or) shallow bedrock units			
Qms/QTm	1,239,404	1.24	0.68
KJf	9,730,882	9.73	5.32
Total, bedrock units	109,702,862	10.97	6.00
Total, Offshore of San Francisco map area	182,881,858	182.88	100.00

DESCRIPTION OF MAP UNITS

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Note that, where older units (typically, bedrock) are overlain by thin (<1 m thick) Quaternary deposits, composite units are mapped. These composite units, which are shown with gray stipple pattern on older unit, are designated by composite label indicating both overlying sediment cover and lower (older) unit, separated by slash (for example, Qms/KJf indicates that thin sheet of Qms overlies KJf)]

as **Artificial seafloor (late Holocene)**—Includes dredge channel and dredge fill; debris at legacy waste-disposal site; and sewage outfall pipe and related rip-rap and scour channel

Qms **Marine nearshore and shelf deposits (late Holocene)—**Predominantly sand (some mud); ripple marks common; found mainly on gently seaward-dipping surface that extends from shoreline to western boundary of map area outside San Francisco ebb-tidal delta

Qmsc **Coarse-grained marine nearshore and Golden Gate channel deposits (late Holocene)—**Predominantly coarse sand, gravel, cobbles, and boulders; found as tidal-current winnowed material at inlet of San Francisco Bay, and as wave-winnowed debris in nearshore adjacent to Ocean Beach; recognized primarily on the basis of low seafloor relief and mottled backscatter, its presence has been variably verified by sampling

Qmsw **Marine sediment wave deposits (late Holocene)**—Sandy sediment organized into large sand waves generated by strong tidal currents (Barnard and others, 2006a,b) at the Golden Gate channel to San Francisco Bay

Qmst **Marine ebb-tidal channel(?) deposits (late Holocene)—**Sandy sediment comprising a semicircular, inward-sloping, smooth seafloor at water depths of about 12 to 24 m; found at mouth of Golden Gate channel to San Francisco Bay

Qmsb **Marine ebb-tidal bar deposits (late Holocene)**—Sandy sediment comprising a horseshoe-shaped bar (“San Francisco Bar”) at about 8 to 12 m water depth outside the mouth of San Francisco Bay; variably hummocky and mottled seafloor texture reflecting influence of both waves and tidal currents

Qmss **Marine shelf scour depressions (late Holocene)**—Inferred to be coarse sand and possibly gravel; found as single depressions or in fields of depressions adjacent to bedrock or interspersed with nearshore sediments offshore Ocean Beach and Muir Beach at water depths of about 10 to 17 m

Qbd **San Francisco Bay deposits (late Holocene)—**Sand-dominated sediment deposited east of Golden Gate channel in San Francisco Bay; strongly influenced by tidal currents

Qbdc **San Francisco Bay deposits, coarse grained (late Holocene)**—Predominantly coarse sand, gravel, cobbles, and boulders; deposited east of Golden Gate channel in San Francisco Bay; strongly influenced by tidal currents

QTm **Merced Formation (Pleistocene and Pliocene)—**Medium-grained to very fine-grained, poorly indurated to friable sandstone, siltstone and claystone, with some conglomerate lenses and a few friable beds of white volcanic ash

KJf **Franciscan Complex, undivided (Cretaceous and Jurassic)**—Mostly sandstone, shale, greenstone, mélange, graywacke, and chert; found in coastal exposures east of San Andreas Fault, including large scour channel beneath Golden Gate Bridge

ONSHORE GEOLOGIC AND GEOMORPHOLOGIC UNITS

[Units are compiled from Bonilla (1961, 1998), Knudsen and others (1997), Brabb and others, (1998), Blake and others (2000), and Witter and others (2006); unit ages, which are from these sources, reflect local stratigraphic relations]

af **Artificial fill (late Holocene)—**Material deposited by humans

afem **Artificial fill over estuarine sediment (late Holocene)—**Material deposited by humans over estuarine sediment

alf **Artificial-levee fill (late Holocene)—**Artificial levees bordering rivers, streams, salt ponds, and sloughs; constructed to contain floodwater or tidal waters

adf **Artificial-dam fill (late Holocene)—**Earth- or rock-fill dams, embankments, and levees; constructed to impound land-locked water bodies

Qf **Alluvial fan deposits (late Holocene)—**Alluvial fan deposits judged to be late Holocene (<1,000 years) in age, on basis of records of historical inundation or presence of youthful braid bars and distributary channels

Qbs **Beach-sand deposits (late Holocene)—**Active beaches in coastal environment; may form veneer over bedrock platform

Qds **Dune sand deposits (Holocene)—**Active dunes and recently stabilized dunes in coastal environments

Qbm **San Francisco Bay mud (Holocene)—**Sediment deposited at or near sea level in the San Francisco Bay estuary that is presently, or was historically, tidal marsh, mud flat, or bay bottom

Qyf **Alluvial fan deposits (Holocene)—**Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains; includes debris-flow, hyperconcentrated-mudflow, and braided-stream deposits

Qa **Alluvial deposits, undivided (Holocene)—**Alluvium; deposited in fan, terrace, or basin environments

Qcl **Colluvium (Holocene)—**Loose to firm, unsorted sand, silt, clay, gravel, rock debris, and organic material, in varying proportions

Qyds **Dune sand (Holocene and late Pleistocene)—**Very well sorted fine to medium grained eolian sand; younger than unit Qds

Qof2 **Older alluvial fan deposits, undivided (Holocene and late Pleistocene)—**Mapped in small valleys where separate fan, basin, and terrace units could not be delineated at the scale of this mapping, and where deposits might be of either late Pleistocene or Holocene age

Qls **Landslide deposits (Holocene and Pleistocene)—**Disintegrated bedrock; physically weathered; ranges from deep-seated landslides to active colluvium

Qof1 **Older alluvial fan deposits (late Pleistocene)—**Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains, including debris flow, hyper-concentrated mudflow, and braided stream deposits; mapped where late Pleistocene age is indicated by greater dissection or soil development than is present on Holocene fans

Qc **Colma Formation (Pleistocene)—**Yellowish-gray and gray to yellowish-orange and red-brown, friable to loose, fine-to medium-grained arkosic sand, with subordinate gravel, silt, and clay. Total thickness unknown, but may be as much as 60 m

QTm **Merced Formation (Pliocene and Pleistocene)—**Medium-gray to yellowish-gray and yellowish-orange, medium- to very fine-grained, poorly indurated to friable sandstone, siltstone, and claystone, with some conglomerate lenses and a few friable beds of white volcanic ash. Formation contains both the Bishop ash (about 760 ka; Sarna-Wojcicki and others, 2000) and the Rockland ash (about 613 ka; Lanphere and others, 1999)

KJf **Franciscan Complex, undivided (Cretaceous and Jurassic**)**—**Mostly graywacke and shale; found east of San Andreas Fault. Locally divided into following subunits:

Kfs **Sandstone and shale in San Bruno Mountain terrane (Cretaceous)**

Kfsm **Massive sandstone (Cretaceous)**

Kfsh **Thin-bedded sandstone and shale (Cretaceous**)

Kfg **Greenstone in Permanente terrane (Cretaceous)**

Kfgwy **Graywacke in Marin Headlands terrane (Cretaceous)**

Kfdb **Diabase in Permanente terrane (Cretaceous)**

KJfy **Metamorphic rocks in Yolla Bolly terrane (Cretaceous and Jurassic)**

KJfch **Chert in Marin Headlands terrane (Cretaceous and Jurassic)**

fsr **Central Belt Mélange (Cretaceous and Jurassic)—**Argillite matrix consisting of sheared mudstone and sandstone; contains variously sized blocks and slabs of greenstone, serpentinite, chert, and other metamorphic rocks. The following units are identified separately where they are large enough to be shown on the map:

sp **Serpentinite (Jurassic)—**considered to be derived from the Coast Range ophiolite

m **Metamorphic rocks (Jurassic)**

Jfmg **Metagreenstone in Yolla Bolly terrane (Jurassic)**

Jfgs **Greenstone in Marin Headlands terrane (Jurassic)**

Acknowledgments

This publication was funded by the California Ocean Protection Council and the U.S. Geological Survey (USGS) Coastal and Marine Geology Program. We thank the officers, crew, and scientific parties of the ships—R/V VenTresca, California State University, Monterey Bay, Seafloor Mapping Lab; F/V Quicksilver, Fugro Pelagos; and R/V Fulmar, National Oceanic and Atmospheric Administration's Monterey Bay National Marine Sanctuary—for their skill and professionalism in collecting the data presented in this report. We thank Patrick Barnard and Bruce Jaffe (both USGS) for their critical reviews that greatly improved this report. The publication benefitted from significant effort Taryn Lindquist put into refining the design of the maps and pamphlet.

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