# California State Waters Map Series—Offshore of Pacifica, California

By Brian D. Edwards, Eleyne L. Phillips, Peter Dartnell, H. Gary Greene, Carrie K. Bretz, Rikk G. Kvitek, Stephen R. Hartwell, Samuel Y. Johnson, Guy R. Cochrane, Bryan E. Dieter, Ray W. Sliter, Stephanie L. Ross, Nadine E. Golden, Janet T. Watt, John L. Chin, Mercedes D. Erdey, Lisa M. Krigsman, Michael W. Manson, and Charles A. Endris

(Susan A. Cochran and Brian D. Edwards, editors)

Pamphlet to accompany

Open-File Report 2014–1260

2014

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: 2014

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Suggested citation:
Edwards, B.D., Phillips, E.L., Dartnell, P., Greene, H.G., Bretz, C.K., Kvitek, R.G., Hartwell, S.R., Johnson, S.Y., Cochrane, G.R., Dieter, B.E., Sliter, R.W., Ross, S.L., Golden, N.E., Watt, J.T., Chin, J.L., Erdey, M.D., Krigsman, L.M., Manson, M.W., and Endris, C.A. (S.A. Cochran and B.D. Edwards, eds.), 2014, California State Waters Map Series—Offshore of Pacifica, California: U.S. Geological Survey Open-File Report 2014–1260, pamphlet 38 p., 10 sheets, scale 1:24,000, *http://dx.doi.org/10.3133/ofr20141260*.

ISSN 2331-1258 (online)

## Contents



## Figures

## Tables



## Map Sheets

# California State Waters Map Series—Offshore of Pacifica, California

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(Susan A. Cochran[1] and Brian D. Edwards,[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

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is published as a PDF file. Geographic information system (GIS) files that contain both ESRI[6] ArcGIS 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 June 10, 2013).

The California Seafloor Mapping Program (CSMP) 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.

[6] Environmental Systems Research Institute, Inc.

# Chapter 1. Introduction

By Brian D. Edwards, H. Gary Greene, Stephanie L. Ross, and John L. Chin

## Regional Setting

The map area offshore of Pacifica, California, which is referred to herein as the "Offshore of Pacifica" map area (figs. 1–1, 1–2), is located in northern California, on the Pacific coast of the San Francisco Peninsula about 10 kilometers south of the Golden Gate. The onshore part of the map area extends from Daly City (population about 101,000) on the north, through Pacifica (population about 37,000), to the small coastal community of Montara (population about 2,900) on the south. Much of the coastal zone is managed by either the State of California or local governments, including the coastal recreational sites at Thornton Beach State Park, Mussel Rock Park, Pacifica State Beach, Gray Whale Cove State Beach, and Montara State Beach (fig. 1–2). Excellent photographic images of this entire coastal region are available at http://www.californiacoastline.org/ (last accessed November 13, 2013).

The Offshore of Pacifica map area straddles the transform boundary between the Pacific and North American tectonic plates, a complex and dynamic geologic setting. The major structure in this plate boundary is the northwest-striking San Andreas Fault, which extends approximately 1,300 km, from Cape Mendocino (about 350 km north of the map area) southward through California to the Gulf of California in Mexico (about 1,000 km south of the map area). Locally, the San Andreas Fault cuts through the map area, crossing the shoreline near Mussel Rock (figs. 1–1, 1–2) before continuing offshore. The San Francisco Bay Area is a well-known seismically active region; the epicenter of the great 1906 California earthquake is located on an offshore section of the San Andreas Fault Zone a few kilometers north of the map area (fig. 1–1; see also, Lomax, 2005).

The Offshore of Pacifica map area is located at the northwest end of the Santa Cruz Mountains part of the California Coast Ranges. Page and others (1998) suggested that much of the Santa Cruz Mountains uplift has happened in the last 400,000 years. Southwest of the San Andreas Fault Zone, this geologically recent uplift has resulted in a highly variable coastal morphology that is characterized by long, narrow beaches bounded by steep cliffs or marine terraces; small pocket beaches surrounded by rocky promontories; and steep, narrow coastal watersheds. Geologic units mapped along the coast include sheared Jurassic to Cretaceous sedimentary, volcanic, and metamorphic rocks of the Franciscan Complex; Cretaceous granitic rocks; friable to indurated Tertiary sedimentary rocks; and Quaternary coastal marine terraces, deep-seated and shallow landslides, and beach and sand dune deposits (see sheet 10; see also, Pampeyan, 1994; Bonilla, 1998; Brabb and others, 1998), all of which contribute sediment to the coastal zone.

In contrast to the coastal zone to the south, which is more rural, the coastal zone in the highly urbanized area north of Mussel Rock and the San Andreas Fault Zone (fig. 1–2) is characterized by a narrow beach bounded by steep, 50- to 120-m-high cliffs made up of friable sands, silts, and clays of the Pliocene and Pleistocene Merced Formation that are the source of numerous landslides. Two recent, large landslide events along "Northridge bluff," near Northridge City Park in Daly City (fig. 1–2; see also, Collins and others, 2007), on December 20, 2003, and January 1, 2007, had estimated volumes of 305,800 to 382,300 $m^3$ and 120,800 $m^3$, respectively.

Coastal landslides also are an issue to the south between Mussel Rock and Mori Point (fig. 1–2; see also, Collins and Sitar, 2008), even as bluffs diminish in height and pocket beaches transition to a more continuous strand that is, in this area, bounded eastward by Quaternary-age dunes and low-lying marine terraces. Mori Point, a coastal promontory in Pacifica underlain by rocks of the Franciscan Complex, rises abruptly to a height of 90 m from the shoreline. Pocket beaches characterize the shoreline from Mori Point south to Shelter Cove, the largest of which, Pacifica State Beach, is at the mouth of San Pedro Creek (fig. 1–2).

The coastal zone south of Pacifica, which stretches from Shelter Cove to Montara and includes Point San Pedro and Devils Slide, lies at the northwest end of San Pedro Mountain (underlain largely by early Tertiary sedimentary rocks) and Montara Mountain (underlain by Cretaceous granitic rocks). Elevations at Montara Mountain exceed 500 m just 4 km from the shoreline, and steep cliffs along the coast are as high as 275 m. This rugged terrain results in numerous rocky promontories, small pocket beaches (for example, Gray Whale Cove State Beach; see fig. 1–2), and large coastal landslides. Slope failures along Devils Slide are notorious for closing California Highway 1, creating such a large and persistent problem that the California Department of Transportation has bypassed this coastal section by tunneling through San Pedro Mountain; the tunnel was completed and the new section of highway opened in 2013. Hapke and Reid (2007, their fig. 22) documented coastal cliff retreat rates of about 0.9 m/yr at Point San Pedro and 1.25 m/yr at Devils Slide. Coastal relief diminishes at Montara in the southernmost part of the map area (fig. 1–2), where the shoreline is bounded by 10- to 20-m-high marine terraces.

Throughout the year, this part of the northern California coast is exposed to four wave climate regimes: the north Pacific swell, the southern swell, northwest wind waves, and local wind waves (Storlazzi and Griggs, 2000; Storlazzi and Wingfield, 2005). The north Pacific swell dominates in winter months (typically, November through March), having wave heights that range from 2 to 10 m at offshore buoys and wave periods that range from 10 to 25 s (National Marine Consultants, 1960; Storlazzi and Wingfield, 2005). During summer months, the largest waves come from the southern swell, generated by storms in the south Pacific and offshore of Central America. Characteristically, these swells have smaller wave heights (0.3–3 m) but similarly long wave periods (10–25 s). Local wind waves are most common from October to April, whereas northwest wind waves affect the coast throughout the year. These two wind-wave regimes typically have wave heights of 1 to 4 m and short wave periods (3–10 s).

Unlike many other parts of the California coast where sediment is supplied primarily from river and (or) stream runoff, sediment supply to the offshore along this part of northern California is a complex mixture of (1) sand transported from the coast north of the Golden Gate, (2) sediment transported to the coast through the San Francisco Bay via the Golden Gate and then dispersed over the adjacent ebb-tide delta (Barnard and others, 2013), and (3) varying volumes of sediment eroded from adjacent steep coastal bluffs caused by wave-induced landslides and other erosional events (Griggs and others, 2005a,b). Additionally, recent studies have documented that, since the 1980s, coastal erosion south of the Golden Gate has increased substantially between Ocean Beach (on the west coast of San Francisco, about 5 km north of the map area) and Point San Pedro (Hapke and others, 2009; Dallas and Barnard, 2011). The combined sediment load is transported southward along the coast (littoral drift) by the generally north-to-south alongshore (littoral) current, which develops in response to the energetic winter-wave climate associated with the north Pacific swell. Overall, beaches in the Offshore of Pacifica map area have a long-term erosional trend (Hapke and others, 2006, their fig. 25), except near Mussel Rock where a long-term accretionary trend may reflect increased sediment supply from landslides. Beach-front riprap armoring and retaining walls are used locally to protect the shoreline from seasonal storm waves, perhaps most notably between Mussel Rock and Mori Point (fig. 1–2).

In the Offshore of Pacifica map area, the continental shelf is about 40 km wide, with water depths at the shelf break that range from about 80 to 120 m. Within California's State Waters (5.6 km; 3 nautical miles), the midshelf to inner shelf areas are characterized by a relatively flat, shallow (water depths of as much as 44 m) seafloor that dips gently (about 0.2° to 0.3°) westward. The seafloor is composed primarily of unconsolidated Holocene sediment (marine deposits), as well as some nearshore bedrock outcrops that consist primarily of rocks of the Tertiary Purisima Formation and also Cretaceous plutonic rocks (granite or granodiorite).

## Publication Summary

This publication about the Offshore of Pacifica 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 seven 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) such as the flat, sediment-covered inner continental to midcontinental shelf, as well as shallow “scour depressions” and local, tectonically controlled bedrock uplifts. 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; this “ground-truth” surveying data is 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 last 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 have 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.

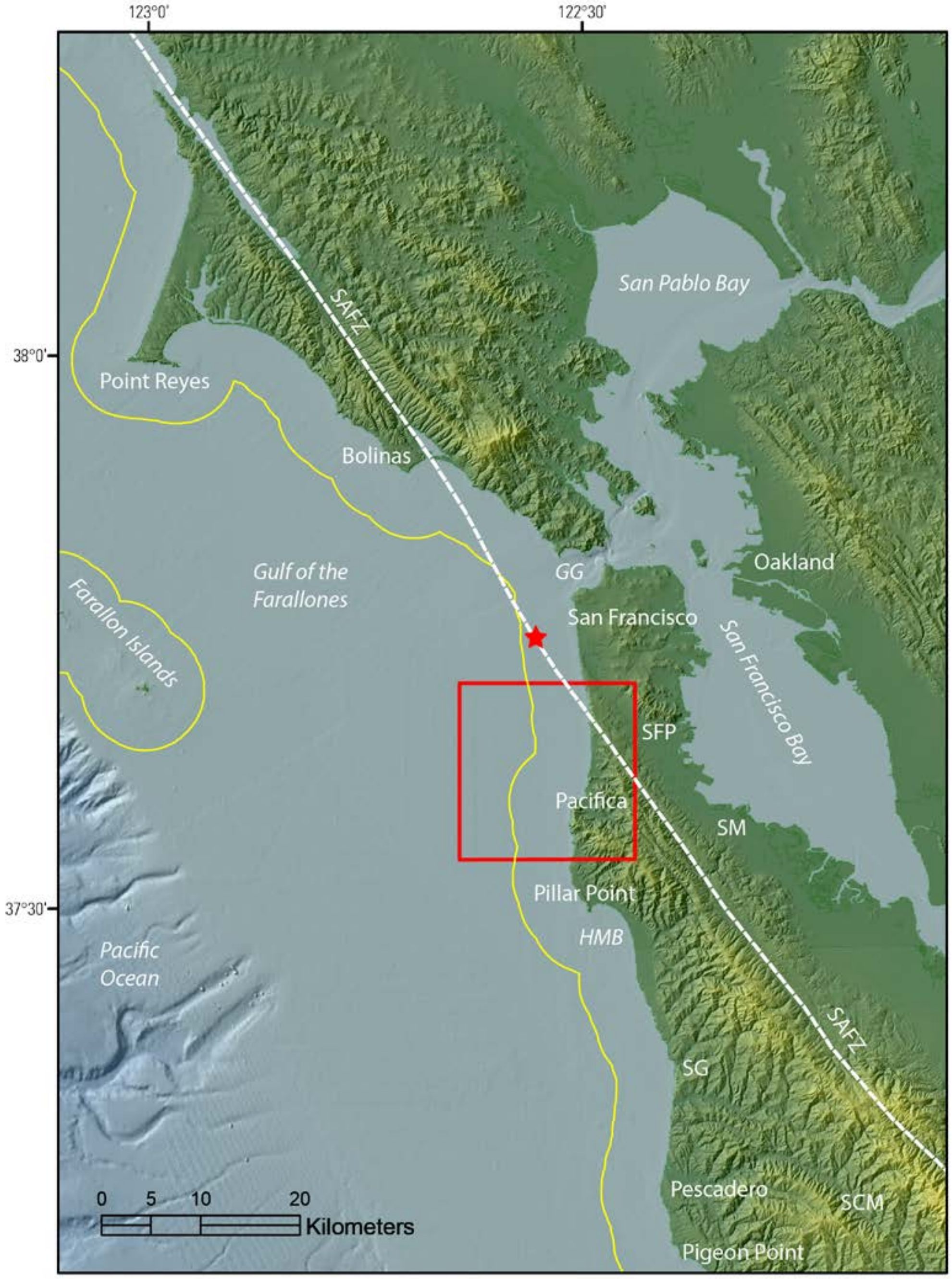


Figure 1–1. Physiography of Bolinas to Pescadero region and its environs. Box shows Offshore of Pacifica map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Red star shows epicenter of great 1906 California earthquake. Other abbreviations: GG, Golden Gate; HMB, Half Moon Bay; SCM, Santa Cruz Mountains; SFP, San Francisco Peninsula; SG, San Gregorio; SM, San Mateo.

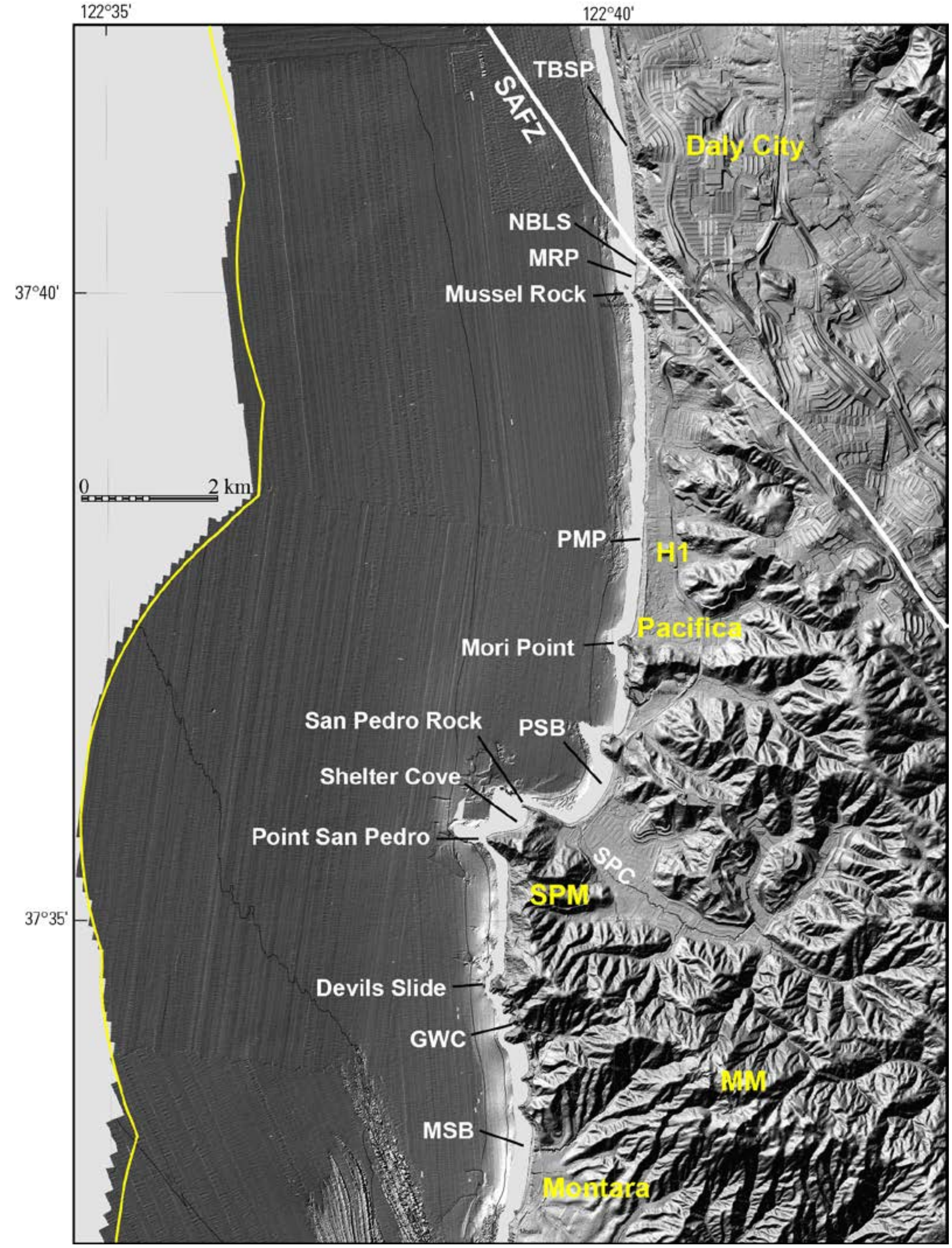


Figure 1–2. Coastal geography of Offshore of Pacifica map area. City of Pacifica extends along coast from Mussel Rock to Shelter Cove. Yellow line shows limit of California's State Waters. Solid white line shows trace of San Andreas Fault Zone (SAFZ). Other abbreviations: GWC, Gray Whale Cove State Beach; H1, Highway 1; MM, Montara Mountain; MRP, Mussel Rock Park; MSB, Montara State Beach; NBLS, "Northridge bluff" landslide; PMP, Pacifica Municipal Pier; PSB, Pacifica State Beach; SPC, San Pedro Creek; SPM, San Pedro Mountain; TBSP, Thornton Beach State Park.

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

By Peter Dartnell, Rikk G. Kvitek, and Carrie K. Bretz

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of Pacifica map area in northern California were generated from bathymetry and backscatter data collected by Fugro Pelagos and by California State University, Monterey Bay (CSUMB) (fig. 1 on sheets 1, 2, 3). The nearshore area was mapped by CSUMB in 2005 and 2007; the areas further offshore, 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.

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 greens to represent greater depths (note that the Offshore of Pacifica map area requires only the shallower part of the full-rainbow color ramp used on some of the other maps in the California State Waters Map Series; see, for example, Kvitek and others, 2012). 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 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 1-m-resolution topographic-lidar data collected by Photoscience in 2005 for the U.S. Geological Survey and the County of San Mateo.

# Chapter 3. Data Integration and Visualization for the Offshore of Pacifica 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 Pacifica 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 Pacifica 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 greens 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, 4, 5, 6, and 7 on sheet 4. These figures highlight the seafloor environments in the Offshore of Pacifica map area, which include large areas of featureless, sediment-covered seafloor interspersed with smaller, complex distributions of coarse-grained sediment and linear outcrops of differentially eroded bedrock.

Video-mosaic images created from digital seafloor video (for example, fig. 3 on sheet 4) display the geologic complexity (rock, sand, and mud; see sheet 10) and biologic complexity of the seafloor. Whereas photographs capture high-quality snapshots of smaller areas of the seafloor (see sheet 6), video mosaics capture larger areas and can show transition zones between seafloor environments. Digital seafloor video is collected from a camera sled towed approximately 1 to 2 meters over the seafloor, at speeds less than 1 nautical mile/hour. Using standard video-editing software, as well as software developed at the Center for Coastal and Ocean Mapping, University of New Hampshire, the digital video is converted to AVI format, cut into 2-minute sections, and desampled to every second or third frame. The frames are merged together using pattern-recognition algorithms from one frame to the next and converted to a TIFF image. The images are then rectified to the bathymetry data using ship navigation recorded with the video and layback estimates of the towed camera sled.

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. 7 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.

# Chapter 4. Seafloor-Character Map of the Offshore of Pacifica Map Area (Sheet 5)

By Eleyne L. Phillips 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 four substrate classes are identified in the Offshore of Pacifica 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)

The seafloor-character map of the Offshore of Pacifica 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://www.csc.noaa.gov/digitalcoast/tools/btm/index.html; 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). 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 four 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 Pacifica map area, only Depth Zones 2 and 3 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 Pacifica map area, only Slope Class 1 is 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 93.0 percent (100.3 $km^2$) of the map area: 72.7 percent (78.4 $km^2$) is in Depth Zone 2, and 20.4 percent (22.0 $km^2$) is in Depth Zone 3. 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 4.6 percent (5.0 $km^2$) of the map area: 4.3 percent (4.6 $km^2$) is in Depth Zone 2, and 0.3 percent (0.4 $km^2$) is in Depth Zone 3. Rock and boulder, rugose (rock outcrops and boulder fields having high surficial complexity) makes up 1.7 percent (1.9 $km^2$) of the map area: 1.4 percent (1.5 $km^2$) is in Depth Zone 2, and 0.3 percent (0.4 $km^2$) is in Depth Zone 3. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than the surrounding seafloor), present only in Depth Zone 2, makes up 0.7 percent (0.7 $km^2$) 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. 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.”

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 Pacifica map area is covered predominantly by Class I sediments mostly composed of sand. Rugose rock outcrops (Class III) and areas of moderately to poorly sorted course sand and gravel (Class II) are located offshore of Point Montara (about 0.5 km south of the map area) and Point San Pedro. The rock outcrops are covered intermittently with varying thicknesses of fine (Class I) to coarse (Class II) sediment. Several smaller areas of scour depressions (Class IV) also have been identified adjacent to rock outcrops.

The classification accuracy of Classes I, III, and IV (86 percent, 70 percent, and 89 percent accurate, respectively; table 4–2) is determined by comparing shipboard video observations, sediment samples, and the classified map. The weaker (34 percent accurate) agreement in Class II (mixed smooth sediment and rock and flat rock outcrop) likely is due to the relatively narrow and intermittent nature of transition zones from sediment to rock and also the size of the buffer; a strong likelihood exists for a Class II (mixed) pixel to be interspersed with pixels belonging to other classes. A single buffered observation locale of 78 pixels, therefore, is likely to be interspersed with other classes of pixels in addition to Class II. Percentages for presence/absence within a buffer also were calculated as a better measure of the accuracy of the classification for patchy rock habitat. The presence/absence accuracy was found to be significant for all classes (94 percent for Class I, 97 percent for Class II, 100 percent for Class III, and 91 percent for Class IV).

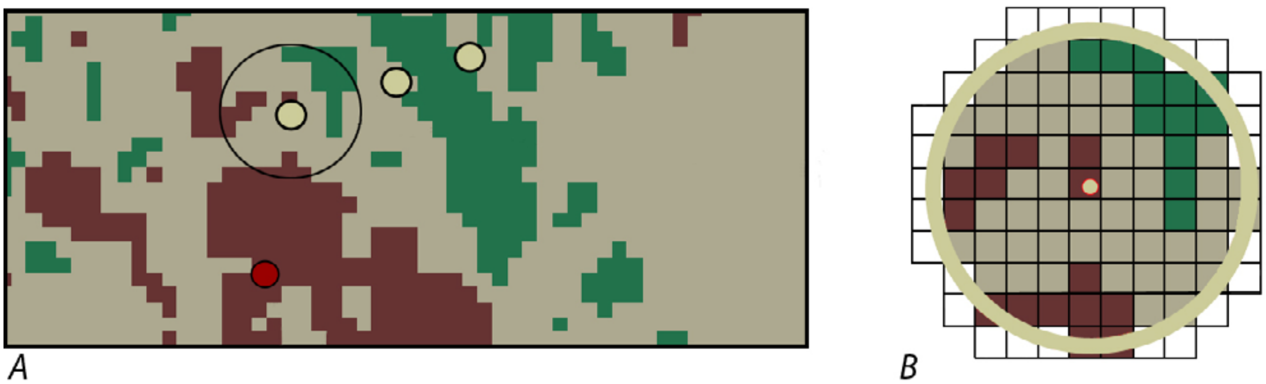


**Figure 4–1.** Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

**Table 4–1.** 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, and IV for use in supervised classification and accuracy assessment in Offshore of Pacifica 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 | trace | |
| sand | sand | low | |
| sand | sand | moderate | |
| sand | shell hash | moderate | |
| | | | sediment |
| | | | ripples |
| Class II | | | |
| cobbles | boulders | low | |
| cobbles | cobbles | low | |
| cobbles | gravel | low | |
| cobbles | rock | low | |
| cobbles | sand | moderate | |
| gravel | gravel | low | |
| rock | rock | low | |
| rock | sand | low | |
| rock | sand | moderate | |
| sand | cobbles | low | |
| sand | gravel | low | |
| sand | gravel | moderate | |
| sand | rock | low | |
| Class III | | | |
| boulders | rock | moderate | |
| cobbles | rock | moderate | |
| rock | rock | high | |
| rock | rock | moderate | |
| Class IV | | | |
| sand | sand | moderate | |
| sand | shell hash | moderate | |
| | | | megaripples |
| | | | oscillatory megaripples |
| | | | depression |

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

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

| Class | Number of observations | % majority | % presence/absence |
|---|---|---|---|
| I—Fine- to medium-grained smooth sediment | 126 | 86.4 | 93.7 |
| II—Mixed smooth sediment and rock | 57 | 34.2 | 96.5 |
| III—Rock and boulder, rugose | 66 | 70.2 | 100.0 |
| IV—Medium- to coarse-grained sediment (in scour depressions) | 22 | 89.4 | 90.9 |

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

By Nadine E. Golden, Brian D. Edwards, 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 Pacifica map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred in 2007. The camera sled was towed 1 to 2 m over the seafloor at speeds of between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 5.39 trackline kilometers of video and 297 still photographs, in addition to 271 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

During the cruise, the USGS camera sled housed two standard-definition (640×480 pixel resolution) video cameras (one forward looking and one downward looking), 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

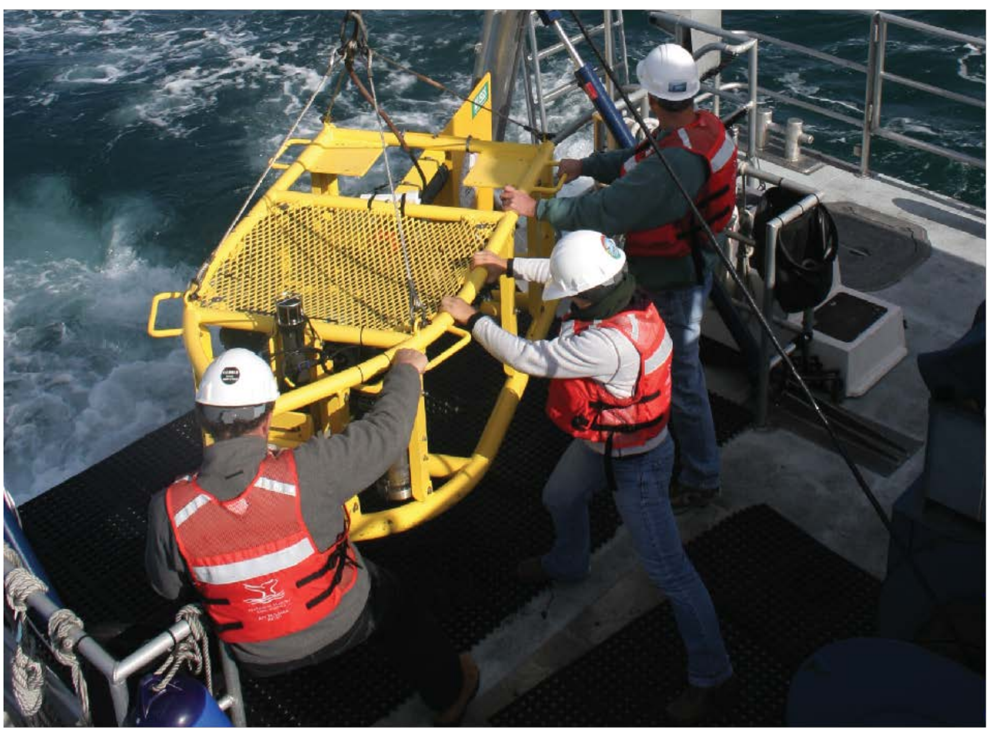

**Figure 5–1.** Photograph of camera sled used in USGS 2007 ground-truth survey.

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, in the Offshore of Pacifica map area, the seafloor surface is predominantly sandy, unconsolidated sediment that is characterized by sharp-crested oscillatory (and often bidirectional) ripple patterns (typical wavelengths, 5 to 15 cm). The video and still photographs document low densities of epifauna, although motile species may have fled the field of view of the camera systems. The general absence of burrows indicates that populations of mega-infauna that are capable of bioturbating the sandy seafloor at a scale observable by our camera systems are sparse and (or) that a dynamic environment of mobile sediment, which degrades or destroys evidence of burrowing, exists. Low abiotic complexity, low biotic complexity, and low percentage of biocover typify the sandy shelf. Rocky outcrops and areas of moderately to poorly sorted, coarse sand and gravel are located immediately offshore of Point Montara (about 0.5 km south of the map area) and Point San Pedro. These areas are characterized by moderate to high abiotic complexity created by steep rocky outcrops that project dramatically above the adjacent sandy seafloor. Here, epifauna can be diverse and schools of rockfish, urchins, starfish (asteroids), as well as numerous attached fauna (for example, sponges and cup corals) provide moderate to high percent biocover. Moderately to poorly sorted, coarse sand and gravel located in these areas typically are shallow depressions relative to the adjacent sandy seafloor. Many of these depressions are characterized by large (more than 1 m) wavelength megaripples composed of coarse sand, fine gravel, and shell debris. These features provide low abiotic complexity and low biotic complexity, and they are characterized by low percent biocover.

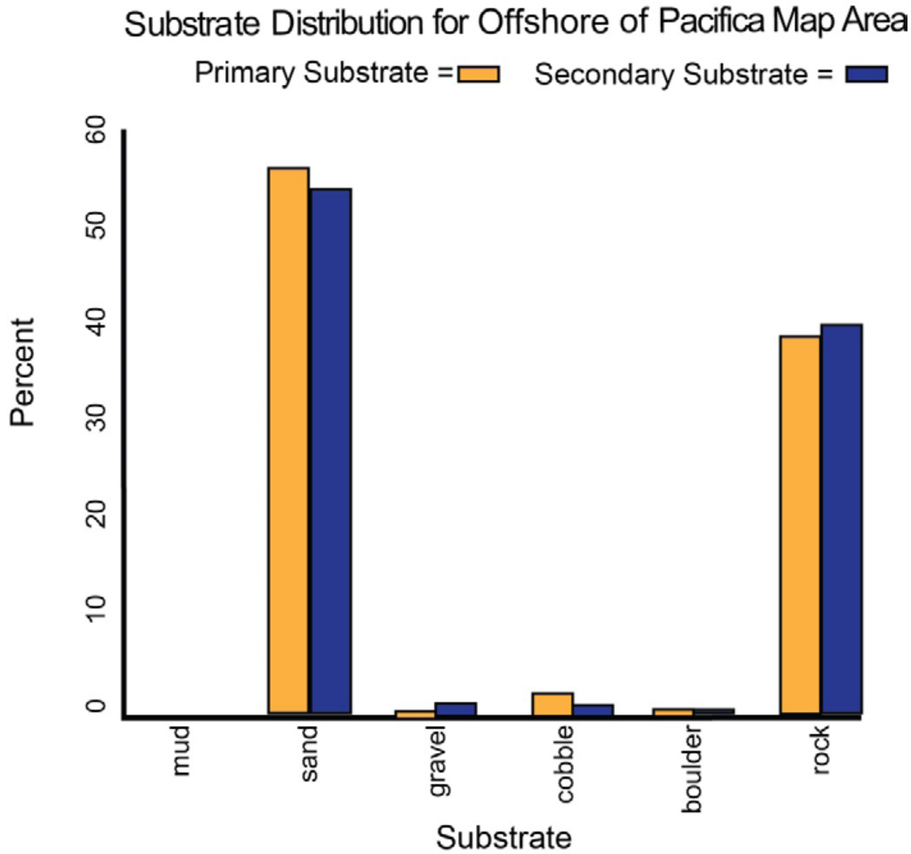


**Figure 5–2.** Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Pacifica map area.

# Chapter 6. Potential Marine Benthic Habitats Map of the Offshore of Pacifica 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 Pacifica 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 Pacifica 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 Pacifica 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 Pacifica 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

Delineated in the Offshore of Pacifica map area are 12 potential marine benthic habitat types, all located on the continental shelf (“Shelf” megahabitat), which is covered primarily with soft, unconsolidated sediment. The meso- and macrohabitats include “hard” deformed sedimentary-rock outcrops and rugose granitic-rock outcrops; “mixed” flat, hard bedrock exposures and (or) boulder and pinnacles that are covered locally with soft, unconsolidated sediment; and dynamic features such as mobile sand sheets and associated scour depressions (“marine shelf scour depressions” of sheet 10). Backscatter data show that the map area is dominated by “soft” sediment, with scattered seafloor bedrock exposures in the nearshore and adjacent to points of land.

Although the Offshore of Pacifica map area is located on the relatively flat, eroded continental shelf, the differentially eroded bedrock areas form the local relief and rugosity that make promising potential habitats for rockfish (*Sebastes* spp.), especially in the southern part of the map area and near Point San Pedro. Sediment transport is primarily to the southeast, and sedimentary processes, which are active in the map area, produce the dynamic bedforms that may be habitats for forage fish such as Pacific sand lance (*Ammodytes hexapterus*). 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), found mainly on the shelf and near points of land.

In the northern part of the map area, unusual areas of localized, scattered, boulderlike features and hummocky seafloor, possibly containing artifacts, were mapped in the nearshore. Although equivocal, these areas are classified as anthropogenic (inferred unit Ss(s/m)a_u?) on the basis of their overall character of irregular multibeam and backscatter returns; however, no ground-truth-survey video or photographic data are available from this area to clarify the interpretation. Seismic-reflection profiles collected from this area and areas farther west document flat-lying reflectors underlying the seafloor (see sheet 8), supporting the contention that, similar to the seafloor to the west, a uniform seafloor is to be expected here. Worth noting is that multibeam and backscatter returns from scattered boulders and (or) irregular deposits could produce this apparent topography, as could electronic artifacts from the multibeam mapping systems. Nevertheless, lacking other data, the existence and scattered appearance of the boulderlike, hummocky, and (or) acoustically irregular features in the multibeam data suggest that anthropogenically dredged or excavated materials might have been dumped in this area.

Of the 107.92 $km^2$ in the map area, only 2.0 $km^2$ (1.9 percent) is exposed hard bedrock, and 0.66 $km^2$ (0.6 percent) consists of sediment-covered bedrock, which is of the mixed hard-soft induration class. Soft, unconsolidated sediment covers a total of 96.5 $km^2$ (89.4 percent). Possibly anthropogenic and hummocky sediment covers 8.75 $km^2$ (8.1 percent) of the map area.

# Chapter 7. Subsurface Geology and Structure of the Offshore of Pacifica 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 Pacifica 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, 4, 6, 8, 9, 10) were collected in 2007 on U.S. Geological Survey (USGS) cruise F–2–07–NC, using the SIG 2Mille minisparker system. This system used a 500-J high-voltage electrical discharge fired 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 m 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).

Data for figure 5 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).

Figure 7 on sheet 8 shows a deep-penetration, migrated, multichannel seismic-reflection profile collected in 1976 by WesternGeco on cruise W–14–76–SF. This profile and other similar data were collected in many areas offshore of California in the 1970s and 1980s when these areas were considered a frontier for oil and gas exploration. Much of these data have been publicly released and are now archived at the U.S. Geological Survey National Archive of Marine Seismic Surveys (U.S. Geological Survey, 2009). These data were acquired using a large-volume air-gun source that has a frequency range of 3 to 40 Hz and recorded with a multichannel hydrophone streamer about 2 km long. Shot spacing was about 30 m. These data can resolve geologic features that are 20 to 30 m thick, down to subbottom depths of about 4 km.

## Geologic Structure and Recent Deformation

The Offshore of Pacifica map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active northwest-striking faults; these include the San Andreas Fault, two major strands of the San Gregorio Fault Zone, and the Potato Patch Fault (see Map E on sheet 9; see also, Bruns and others, 2002; Ryan and others, 2008). Faults in the offshore part of the map area are identified on seismic-reflection profiles on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as reflection presence, amplitude, frequency, geometry, continuity, and vertical sequence.

The San Andreas Fault, which is the dominant plate-boundary structure, extends offshore near Mussel Rock, where it continues northwest for about 30 km before coming onshore again at Bolinas (Map E on sheet 9). Most of the Offshore of Pacifica map area lies southwest of this fault, along strike with the young, high topography of the Santa Cruz Mountains and Coast Ranges (Maps C, D, E on sheet 9). This regional uplift has been linked to a northwest-transpressional bend in the San Andreas Fault (Zoback and others, 1999). The San Andreas Fault in the 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, another major strike-slip fault system within the distributed transform plate boundary, extends predominantly in the offshore for about 400 km from Point Conception in the south (where it is known as the Hosgri Fault) to Bolinas and Point Reyes in the north (Dickinson and others, 2005). Cumulative lateral slip on the San Gregorio Fault in this area is estimated to be about 4 to 10 mm/yr (U.S. Geological Survey and California Geological Survey, 2010). In the Offshore of Pacifica map area, the San Gregorio Fault forms a distributed shear zone in the offshore that includes two main faults, an east strand and a west strand, that are known to the south as the Seal Cove Fault and the Frijoles Fault, respectively (Weber and Lajoie, 1980; Brabb and others, 1998).

Map E shows the regional pattern of major faults and earthquakes. Fault location is simplified and compiled from our mapping within California's State Waters (see sheet 10) and from the U.S. Geological Survey's Quaternary fault and fold database (U.S. Geological Survey and California Geological Survey, 2010). Earthquake epicenters are from the Northern California Earthquake Data Center (2014), which is maintained by the U.S. Geological Survey 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 number of earthquakes in the region clearly occur within the broad San Andreas Fault Zone between Pacifica and Bolinas; events west of the east strand of the San Gregorio Fault 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 (see, for example, Bolt, 1968; Lomax, 2005), a few kilometers north of the map area.

## Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Pacifica map area, herein considered part of the Pacifica-Pescadero shelf. This shelf (see Maps A, B on sheet 9), which in the map area is relatively flat (less than 0.4°) and shallow (less than 40 m), is 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 Offshore of Pacifica map area was emergent and the shoreline was more than 45 km west of San Francisco, near the Farallon Islands. The post-LGM sea-level rise was rapid (about 9 to 11 m per thousand years) until about 7,000 years ago, when it slowed considerably to about 1 m per thousand years (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006; Gornitz, 2009).

The sediments deposited during this latest Pleistocene and Holocene sea-level rise are shaded blue in the seismic-reflection profiles on sheet 8 (figs. 1, 2, 3, 4, 6, 8, 9, 10). This post-LGM stratigraphic unit is 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 extensive wave winnowing, resulting in a uniform sediment grain size, hence, the lack of acoustic-impedance contrasts needed to produce seismic reflections. The contact between these sediments and the underlying strata is a transgressive erosional surface, which commonly is 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 both acoustic transparency and by “acoustic masking,” which is associated with the presence of interstitial gas within the sediment (see, for example, Fader, 1997).

## 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 Pacifica 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 Point (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 (see sheet 10), and contoured following the methodology of Wong and others (2012).

Several factors required manual editing of the preliminary sediment-thickness maps to make the final product. The San Andreas, San Gregorio, Potato Patch, and Golden Gate 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 final regional sediment-thickness map (Wong and others, 2012). 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 Pacifica map area ranges from 0 to 14 m (Map B on sheet 9), and the depth to the base of this unit ranges from less than 10 to 53 m (Map A on sheet 9). The most rapid changes in thickness are in the southern part of the map area and are associated with the west strand of the San Gregorio Fault. Mean sediment thickness for the map area is 4.4 m, and the total sediment volume is $468{\times}10^6$ $m^3$ (table 7–1). The relatively thin sediment cover in most of the map area suggests a lack of sediment “accommodation space” (Catuneanu, 2006), which is consistent with regional uplift. The uplift raises and exposes much of the shallow shelf to the high wave energy that is characteristic of this region (Barnard and others, 2007), so that sediments are efficiently reworked and transported off the inner shelf and midshelf areas 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 Pacifica 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) 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 Pacifica 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 Pacifica map area | | | |
| Offshore of Pacifica map area | 106 | 4.4 | 468 |

# Chapter 8. Geologic and Geomorphic Map of the Offshore of Pacifica Map Area (Sheet 10)

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## Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Pacifica 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 Brabb and others (1998) and Witter and others (2006). Unit ages, which are derived from these sources, reflect local stratigraphic relations.

The continental shelf within California's State Waters in the Offshore of Pacifica map area is shallow (less than about 40 m) and flat with a very gentle (less than 0.5°) offshore dip. Shelf morphology and evolution are the result of the interplay between local tectonics, sea-level rise, sedimentary processes, and oceanography. Tectonic influences are related to local faulting and uplift. Sea level has risen about 125 to 130 m over the last about 21,000 years (see, for example, Lambeck and Chappell, 2001; Gornitz, 2009), leading to the progressive eastward migration (a few tens of kilometers) of the shoreline and wave-cut platform and the associated transgressive erosion and deposition (see, for example, Catuneanu, 2006). The Offshore of Pacifica map area is now mainly an open-ocean shelf that is subjected to the full, and sometimes severe, wave energy and strong currents of the Pacific Ocean (Storlazzi and Wingfield, 2005; Barnard and others, 2007). Most of the offshore is covered by marine sediments; artificial fill (unit af) is mapped only at the Pacifica Municipal Pier and at the south end of Pacifica State Beach.

Given the relatively shallow depths and high energy, modern shelf deposits are mostly sand (unit Qms). Coarser grained sands and gravels (units Qmss and Qmsc) are recognized primarily on the basis of bathymetry and high backscatter (sheets 1, 2, 3). Unit Qmsc is mapped as nearshore bars (less than 12 m water depth) for about 2 km along the coast north of Mussel Rock and in a few local places just offshore of the southern part of Pacifica, as well as in two isolated patches farther offshore, at about 25 m water depth. Unit Qmss forms erosional lags in scour depressions (see, for example, Cacchione and others, 1984) at water depths of about 15 to 25 m, in contact with offshore bedrock uplifts and unit Qms. Such scour depressions are common along this stretch of the California coast (see, for example, Cacchione and others, 1984; Hallenbeck and others, 2012; Davis and others, 2013) where offshore sandy sediment can be relatively thin (and, thus, is unable to fill the depressions) owing to lack of sediment supply from rivers and also to significant erosion and offshore transport of sediment during large northwest winter swells. Although the general areas in which both unit Qmss scour depressions and unit Qmsc nearshore bars and scattered patches are found are not likely to change substantially, the boundaries of the unit(s) likely are ephemeral, changing seasonally and during significant storm events.

Offshore bedrock outcrops are mapped as the undivided Jurassic and Cretaceous Franciscan Complex (unit KJf); the Cretaceous granitic rocks of Montara Mountain (unit Kgr); undivided Cretaceous and (or) Tertiary bedrock (unit TKu); the unnamed sandstone, shale, and conglomerate unit of Paleocene age (Tss); the Miocene and Pliocene Purisima Formation (unit Tp); undivided sedimentary rocks of Paleocene, Miocene and Pliocene, or Pliocene and Pleistocene age (unit QTu); and Pliocene and Pleistocene strata of the Merced Formation (unit QTm). These units are delineated by extending outcrops and trends from mapped onshore geology; by their distinctive surface textures as revealed by high-resolution bathymetry (see sheets 1, 2); and also by seismic-reflection profiles, which allow distinction of layered, relatively undeformed sedimentary bedrock from more massive and deformed basement rocks. For example, outcrops of the Purisima Formation form distinctive, straight to curved "ribs" caused by differential erosion of more and less resistant lithologies (for example, sandstone and mudstone). In contrast, granitic rocks have a densely cross-fractured surface texture, and rocks of both the Franciscan Complex and the Paleocene unnamed sandstone, shale, and conglomerate unit have a more massive, more irregular, and smoother surface texture. Outcrops of the Purisima Formation are mapped in water as deep as 35 m, whereas other bedrock units are found in shallower (less than 20 m) water depths, most commonly adjacent to coastal promontories underlain by bedrock (for example, Mussel Rock, Mori Point, Point San Pedro, and south of Montara State Beach).

Areas where shelf sediments form thin (less than 2 m) veneers over low-relief rocks of the Franciscan Complex, the undivided Tertiary sedimentary rocks unit, or the Merced Formation are mapped as units Qms/KJf, Qms/QTu, and Qms/QTm, respectively. These composite units are recognized on the basis of the combination of flat relief, continuity with moderate- to high-relief bedrock outcrops, high-resolution seismic-reflection data (see sheet 8), and (in some cases) moderate to high backscatter. Overlying sediment is interpreted as an ephemeral and dynamic sediment layer that may or may not be continuously present at a specific location, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term climate cycles. Storlazzi and others (2011) described the seasonal burial and exhumation of submerged bedrock in a similar high-energy setting in northern Monterey Bay, about 80 km south of the map area. The relative proportions of all offshore map units are shown in table 8–1.

The Offshore of Pacifica map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active northwest-striking faults; these include the San Andreas Fault and the San Gregorio Fault Zone (Bruns and others, 2002; Ryan and others, 2008). The offshore parts of these faults, which are buried by sediment and, thus, have no surface expression, have been mapped on the basis of seismic-reflection data (see sheet 8). The San Andreas Fault, which is the dominant plate-boundary structure, extends offshore near Mussel Rock. The San Andreas Fault in the map 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) is thought to have nucleated on the San Andreas Fault a few kilometers north of the map area, offshore of San Francisco (see, for example, Bolt, 1968; Lomax, 2005).

The San Gregorio Fault, another major strike-slip fault system within the transform plate boundary, extends predominantly in the offshore for about 400 km from Point Conception in the south (where it is known as the Hosgri Fault) to Bolinas and Point Reyes in the north (McCulloch, 1987; Dickinson and others, 2005). Cumulated lateral slip is estimated to be about 4 to 10 mm/yr (U.S. Geological Survey and California Geological Survey, 2010). In the Offshore of Pacifica map area, the San Gregorio Fault forms a distributed, 2- to 3-km-wide shear zone in the offshore that includes two main faults, an east strand and a west strand, that are known to the south as the Seal Cove Fault and the Frijoles Fault, respectively (Weber and Lajoie, 1980; Brabb and others, 1998). The east strand juxtaposes Cretaceous granitic rocks to the east and rocks of the Purisima Formation to the west; the west strand is inferred to juxtapose the Purisima Formation to the east and undivided Cretaceous and (or) Tertiary bedrock to the west.

**Table 8–1.** Areas and relative proportions of offshore geologic map units in Offshore of Pacifica map area.

| Map Unit | Area ($m^2$) | Area ($km^2$) | Percent of total area |
|---|---|---|---|
| Marine sedimentary units | | | |
| Qms | 97,142,518 | 97.14 | 87.70 |
| Qmsc | 908,547 | 0.91 | 0.82 |
| Qmss | 776,326 | 0.78 | 0.70 |
| Total, sedimentary units | 98,827,391 | 98.83 | 89.22 |
| Marine bedrock and (or) shallow bedrock units | | | |
| Qms/QTm | 1,873,823 | 1.87 | 1.69 |
| Qms/QTu | 6,416,454 | 6.42 | 5.79 |
| Qms/KJf | 139,064 | 0.14 | 0.13 |
| QTu | 35,807 | 0.04 | 0.03 |
| Tp | 1,713,667 | 1.71 | 1.55 |
| Tss | 527,752 | 0.53 | 0.48 |
| TKu | 29,728 | 0.03 | 0.03 |
| Kgr | 377,358 | 0.38 | 0.34 |
| KJf | 827,799 | 0.83 | 0.75 |
| Total, bedrock units | 11,941,453 | 11.94 | 10.78 |
| Total, Offshore of Pacifica map area | 110,768,844 | 110.77 | 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 or yellow 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)]

af **Artificial fill and anthropogenic material (late Holocene)—** Rock, sand, and mud. Placed, dredged, or substantially modified by human activity; includes pipelines

Qms **Marine nearshore and shelf deposits (late Holocene)**—Predominantly sand (some mud); ripple marks common; found on seaward-dipping surface that extends from shoreline to west edge of map area

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 elevated shelf sediments (unit Qms). General area in which unit is found is not likely to change substantially, but boundaries of unit(s) and locations of individual depressions (and intervening flat sheets of unit Qms) likely are ephemeral, changing during significant storm events

Qmsc **Coarse-grained marine nearshore and shelf deposits (late Holocene)**—Predominantly coarse sand, gravel, cobbles, and boulders; found on gently seaward-dipping (less than 1°) surface in water depths typically less than about 20 m; recognized primarily on basis of variable and mottled backscatter

QTm **Merced Formation (Pleistocene and Pliocene)**—Medium-gray to yellowish-gray and yellowish-orange, 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. 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). Stippled areas (composite unit Qms/QTm) indicate where thin sheets of Qms overlie unit

QTu **Sedimentary rocks, undivided (Pleistocene and Pliocene, Pliocene and Miocene, or Paleocene)—**May consist of rocks of the Merced Formation and (or) the Purisima Formation and (or) the unnamed Paleocene sandstone, shale, and conglomerate unit. Stippled areas (composite unit Qms/QTu) indicate where thin sheets of Qms overlie unit

Tp **Purisima Formation (Pliocene and late Miocene)**—Predominantly gray and greenish-gray to buff, fine-grained marine sandstone, siltstone, and mudstone; also includes some porcelaneous shale and mudstone, chert, silty mudstone, and volcanic ash

Tss **Unnamed sandstone, shale, and conglomerate (Paleocene)**—Rhythmically alternating beds of sandstone and shale

TKu **Bedrock, undivided (Tertiary and (or) Cretaceous)**—Possibly includes rocks of the Pliocene and Miocene Purisima Formation (unit Tp) or Cretaceous granitic rocks (Kgr)

Kgr **Granitic rocks of Montara Mountain (Cretaceous)**—Very light gray to light-brown, medium-crystalline to coarsely crystalline, foliated granitic rock; largely quartz diorite with some granite; highly fractured and deeply weathered

KJf **Franciscan Complex, undivided (Cretaceous and Jurassic**)—Predominantly graywacke and shale; also includes sandstone, greenstone, chert, limestone, sheared rock (mélange), and serpentinite. Stippled areas (composite unit Qms/KJf) indicate where thin sheets of Qms overlie unit

## ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

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

af **Artificial fill (late Holocene)**— Rock, sand, and mud; material deposited by humans

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

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

ac **Artificial stream channels (late Holocene)**—Modified stream channels; includes straightened or realigned channels, flood-control channels, and concrete canals

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

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

Qa **Alluvial deposits, undivided (late Holocene)**—Fluvial sediment; judged to be late Holocene (<1,000 years) in age, on basis of records of historical inundation, as well as identification of youthful meander scars and (or) braid bars on aerial photographs, orthophoto quadrangles, or lidar-based shaded-relief maps

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

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

Qed **Estuarine-delta deposits (Holocene)**—Heterogeneous mixture of coarse and fine estuarine sediment; deposited in delta at mouths of tidally influenced coastal streams, where fresh water mixes with seawater

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

Qya **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

Qds **Dune sand (Holocene and late Pleistocene)**—Very well sorted, fine- to medium-grained eolian sand

Qof2 **Older alluvial fan deposits (Holocene and late Pleistocene)**—Sand, gravel, silt, and clay on gently sloping, fan-shaped, relatively undissected alluvial surfaces

Qof1 **Older alluvial fan deposits, undivided (Holocene and late Pleistocene)**—Mapped in small valleys where separate fan, basin, and terrace deposits could not be delineated at map scale, as well as where deposits might be of either Holocene or late Pleistocene age

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

Qoa **Older alluvial deposits, undivided (late Pleistocene)**—Mapped on gently sloping to level alluvial fan or terrace surfaces or where separate units could not be delineated at map scale; late Pleistocene age is indicated by depth of stream incision, degree of soil development, and lack of historical flooding

Qmt **Marine-terrace deposits, undivided (Pleistocene)**—Sand and gravel, deposited on uplifted marine-abrasion platforms along coast. Local relative ages designated by numbers from youngest (Qmt3) to oldest (Qmt1)

Qmt3 **Marine-terrace deposits (Pleistocene)**—Sand and gravel, deposited on uplifted marine-abrasion platforms along coast

Qmt2 **Marine-terrace deposits (Pleistocene)**—Sand and gravel, deposited on uplifted marine-abrasion platforms along coast

Qmt1 **Marine-terrace deposits (Pleistocene)**—Sand and gravel, deposited on uplifted marine-abrasion platforms along coast

Qc **Colma Formation (Pleistocene)**—Yellowish-gray and gray to yellowish-orange and reddish-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 (Pleistocene and Pliocene)**—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)

Tss **Unnamed sandstone, shale, and conglomerate (Paleocene)**—Rhythmically alternating beds of sandstone and shale, with discontinuous boulder and cobble conglomerate lenses near middle of section and some pebble conglomerate beds near base of section on Montara Mountain

Kgr **Granitic rocks of Montara Mountain (Cretaceous)**—Very light gray to light-brown, medium-crystalline to coarsely crystalline, foliated granitic rock; largely quartz diorite with some granite; highly fractured and deeply weathered

KJf **Franciscan Complex, undivided (Cretaceous and Jurassic**)—Mostly graywacke and shale. Locally divided into following subunits:

fs **Sandstone and shale**—Greenish-gray to buff, fine- to coarse-grained sandstone (graywacke), with interbedded siltstone and shale

fg **Greenstone**—Dark-green to red, altered basaltic rocks, including flows, pillow lavas, breccias, tuff breccias, tuffs, and minor related intrusive rocks

fc **Chert**—White, green, red, and orange chert; in places, interbedded with reddish-brown shale. Chert and shale commonly are rhythmically banded in thin layers, although chert may crop out in very thick layers

fl **Limestone**—Light-gray, finely to coarsely crystalline limestone, in lenticular bodies; commonly surrounded by greenstone of the Franciscan Complex

fsr **Sheared rock (mélange)**—Predominantly graywacke, siltstone, and shale, substantial portions of which have been sheared; also includes hard blocks of all other rock types of the Franciscan Complex

sp **Serpentinite**—Greenish-gray to bluish-green, sheared serpentinite; encloses variably abundant blocks of unsheared rock

## 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, Jonathan Warrick, and Scott Starratt (all USGS) for their critical reviews that greatly improved this report. We are very grateful to USGS editor Taryn Lindquist for helping us develop the templates and formats for this series of publications, and for invaluable editorial review and suggestions.

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