California State Waters Map Series—Offshore of Half Moon Bay, California

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

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

Pamphlet to accompany

Open-File Report 2014–1214

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 Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014

Suggested citation:
Cochrane, G.R., Dartnell, P., Greene, H.G., Johnson, S.Y., Golden, N.E., Hartwell, S.R., Dieter, B.E., Manson, M.W., Sliter, R.W., Ross, S.L., Watt, J.T., Endris, C.A., Kvitek, R.G., Phillips, E.L., Erdey, M.D., Chin, J.L., and Bretz, C.K. (G.R. Cochrane and S.A. Cochran, eds.), 2014, California State Waters Map Series—Offshore of Half Moon Bay, California: U.S. Geological Survey Open-File Report 2014–1214, pamphlet 37 p., 10 sheets, scale 1:24,000, *http://dx.doi.org/10.3133/ofr20141214*.

ISSN 2331-1258 (online)

Contents

Figures

Tables

Map Sheets

California State Waters Map Series—Offshore of Half Moon Bay, California

By Guy R. Cochrane,[1] Peter Dartnell,[1] H. Gary Greene,[2] Samuel Y. Johnson,[1] Nadine E. Golden,[1] Stephen R. Hartwell,[1] Bryan E. Dieter,[2] Michael W. Manson,[3] Ray W. Sliter,[1] Stephanie L. Ross,[1] Janet T. Watt,[1] Charles A. Endris,[2] Rikk G. Kvitek,[4] Eleyne L. Phillips,[1] Mercedes D. Erdey,[1] John L. Chin,[1] and Carrie K. Bretz[4]

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

Preface

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

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

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

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

---

[1] U.S. Geological Survey
[2] Moss Landing Marine Laboratories, Center for Habitat Studies
[3] California Geological Survey
[4] California State University, Monterey Bay, Seafloor Mapping Lab
[5] Environmental Systems Research Institute, Inc.

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 Game, the California Geological Survey, California State University at Monterey Bay's Seafloor Mapping Lab, Moss Landing Marine Laboratories Center for Habitat Studies, Fugro Pelagos, Pacific Gas and Electric Company, National Oceanic and Atmospheric Administration (NOAA, including National Ocean Service – Office of Coast Surveys, National Marine Sanctuaries, and National Marine Fisheries Service), U.S. Army Corps of Engineers, the Bureau of Ocean Energy Management, the National Park Service, and the U.S. Geological Survey.

Chapter 1. Introduction

By Guy R. Cochrane

Regional Setting

The map area offshore of the city of Half Moon Bay, California, which is referred to herein as the "Offshore of Half Moon Bay" map area (figs. 1–1, 1–2) is located in northern California, on the Pacific Coast of the San Francisco Peninsula about 40 kilometers south of the Golden Gate. The city of Half Moon Bay (population, about 11,000) is the nearest significant onshore cultural center (fig. 1–1). The Pillar Point Harbor at the north edge of Half Moon Bay offers a protected landing for boats and provides other marine infrastructure. The harbor, which was formed by the construction of two riprap jetties, is managed by the San Mateo County Harbor District. The harbor has 369 berthing slips and supports a commercial fishing fleet and search-and-rescue services.

The Offshore of Half Moon Bay map area lies offshore of the Santa Cruz Mountains (fig. 1–1), part of the northwest-trending Coast Ranges that run roughly parallel to the San Andreas Fault Zone (California Geological Survey, 2002a). The western margin of North America is the only continental margin in the world delineated largely by transform faults such as the San Andreas Fault (Dickinson, 2004). The Santa Cruz Mountains lie between the San Andreas Fault Zone and the San Gregorio Fault system.

Such faults have played an important role in the development of the map area. The flat coastal area (the most recent of numerous marine terraces) was formed by wave erosion about 105 thousand years ago (Weber, 1990). The higher elevation of this same terrace west of the Half Moon Bay airport is caused by uplift on the Seal Cove Fault, a splay of the San Gregorio Fault Zone (see sheet 10). Although originally incised into the rising terrain horizontally, the ancient terrace surface has been gently folded into a northwest-plunging syncline by compression related to right-lateral strike-slip movement along the San Gregorio Fault Zone (Weber, 1990). The lowest elevation coincides with the deepest part of the embayment at Half Moon Bay; the terrace surface rises both to the north and to the south (Lajoie, 1986).

A westward bend in the San Andreas Fault Zone, coupled with right-lateral movement along the Seal Cove Fault (Weber, 1990), which comes ashore in Pillar Point Harbor (Dickinson and others, 2005), has resulted in the folding and uplifting of sedimentary rocks of the Purisima Formation in the offshore, forming the folds and faults that are visible on the seafloor from the headland at Pillar Point (see sheet 10). Differential erosion of the folded layers of the Purisima Formation has exposed the parallel curved-rock ridges that are visible on the seafloor and in the bathymetry data (see sheets 1, 2).

Exposures of granitic rocks of the Salinian block are found in the Moss Beach area north of Pillar Point, east of the San Gregorio Fault (see sheet 10). In the Bolinas to Pescadero region, Salinian block granitic rocks lie between the San Gregorio Fault system and the San Andreas Fault Zone, and they likely are part of a block that has been transported approximately 155 km north from the south end of the Sierra Nevada batholith by motion along the San Andreas transform fault system (Dickinson and others, 2005).

Uplift in this map area has resulted in relatively shallow water depths within California's State Waters (0 to 55 m) and, thus, little accommodation space for sediment accumulation. Sediment is observed in the shelter of Half Moon Bay and on the outer half of the California's State Waters shelf. Sediment in the area is mobile, often forming dunes and sand waves.

The Offshore of Half Moon Bay map area lies near the midpoint of the San Francisco littoral cell (Hapke and others, 2006), which is characterized by north-to-south littoral transport of sediment that is derived mainly from San Francisco Bay, ephemeral streams, and local coastal erosion. Offshore beyond California's State Waters, unnamed canyons that incise the slope have been disconnected from coastal streams by the rising sea level, which has risen about 125 m since the lowstand associated with the Last Glacial Maximum, about 18,000 to 20,000 years ago (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Lambeck and others, 2002). In the map area, no major submarine canyons extend beyond the shelf break up into the nearshore to receive littoral drift.

Griggs and others (2005) categorized erosion of the coastline in the map area as either moderate or high risk as opposed to stable low risk. From north to south, types of erosion include (1) cliff erosion from wave attack along the exposed northern coast, (2) erosion at the east end and south of the harbor breakwater owing to the refraction of wave energy by the breakwater, and (3) erosion around armored shoreline in the Miramar Beach area (fig. 1–1).

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

The Offshore of Half Moon Bay map area lies within the Shelf (continental shelf) megahabitat of Greene and others (1999). Habitats range from significant rocky outcrops that support kelp-forest communities nearshore to rocky-reef communities in deep water. Biological productivity resulting from coastal upwelling supports populations of Sooty Shearwater (*Puffinus griseus*), Western Gull (*Larus occidentalis*), Common Murre (*Uria aalge*), Cassin’s Auklet (*Ptychoramphus aleuticus*), and many other less populous bird species (Ainley and Hyrenbach, 2010). In addition, an observable recovery of Humpback and Blue Whales (*Megaptera novaeangliae* and *Balaenoptera musculus*, respectively) has occurred in the area; both species are dependent on coastal upwelling to provide nutrients (Calambokidis and Barlow, 2004). The large extent of exposed inner shelf bedrock supports large forests of “bull kelp” (*Nereocystis luetkeana*) (Miller and Estes, 1989), which is well adapted for high wave-energy environments (Koehl and Wainwright, 1977). Common fish species found in the kelp beds and rocky reefs include blue rockfish (*Sebastes mystinus*), black rockfish (*Sebastes melanops*), olive rockfish (*Sebastes serranoides*), kelp rockfish (*Sebastes atrovirens*), gopher rockfish (*Sebastes carnatus*), black-and-yellow rockfish (*Sebastes chrysomelas*), painted greenling (*Oxylebius pictus*), kelp greenling (*Hexagrammos decagrammus*), and lingcod (*Ophiodon elongatus*) (Stephens and others, 2006).

Wind directions along the northern California coast typically are from the west-northwest; however, during the winter, strong North Pacific storms generate large, long-period waves from more westerly directions that shoal and break over the bedrock reef offshore of Pillar Point Harbor at the world-famous surfing location known as Mavericks. Waves can routinely crest at over 7.5 m during these conditions and may reach 24 m.

Publication Summary

This publication about the Offshore of Half Moon Bay map area includes ten map sheets that contain explanatory text, in addition to this descriptive pamphlet and a data catalog of geographic information system (GIS) files. Sheets 1, 2, and 3 combine data from four different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data reveal a range of physiographic features (highlighted in the perspective views on sheet 4) 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.

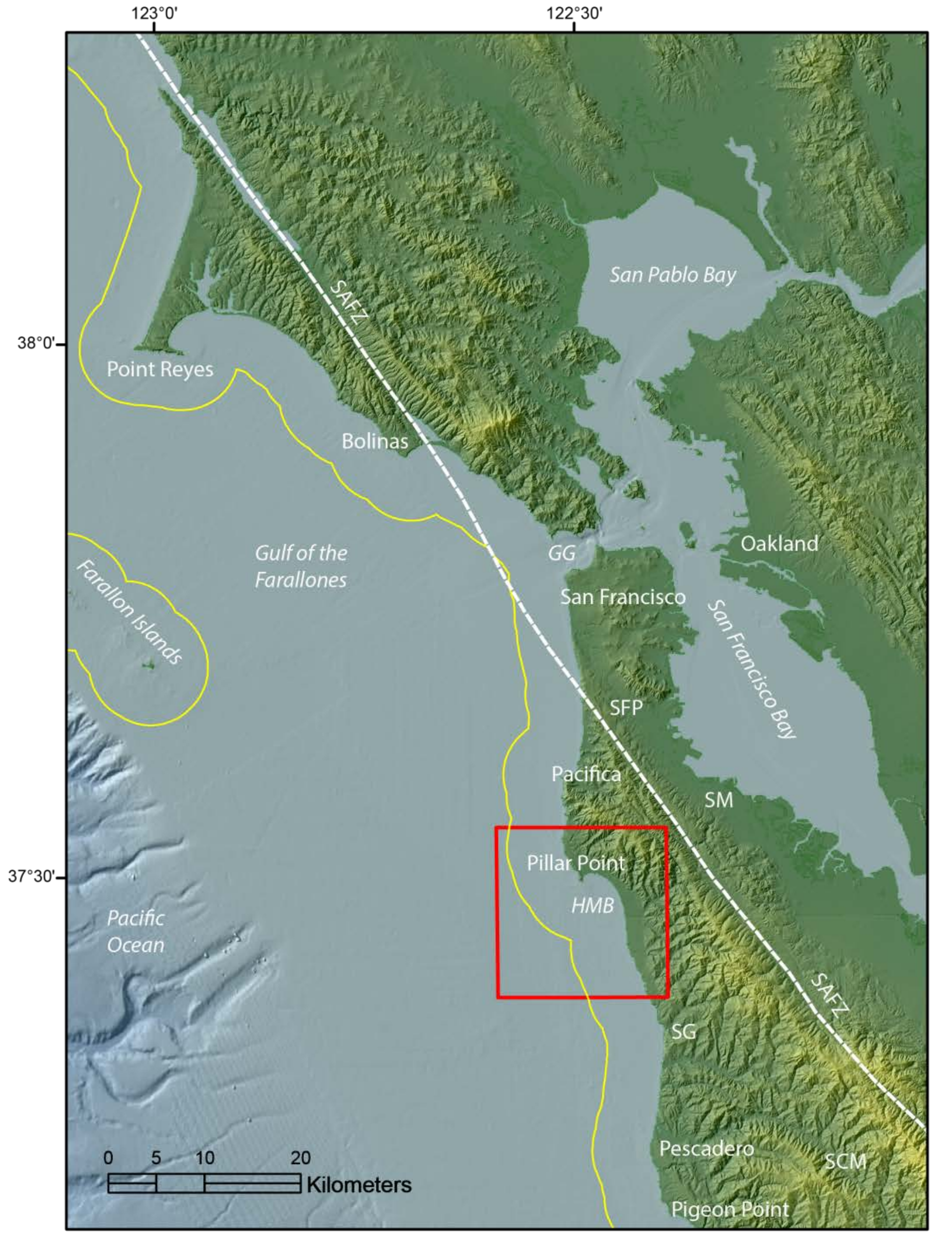

Figure 1–1. Physiography of Bolinas to Pescadero region and its environs. Box shows Offshore of Half Moon Bay map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Other abbreviations: GG, Golden Gate; HMB, Half Moon Bay; SCM,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

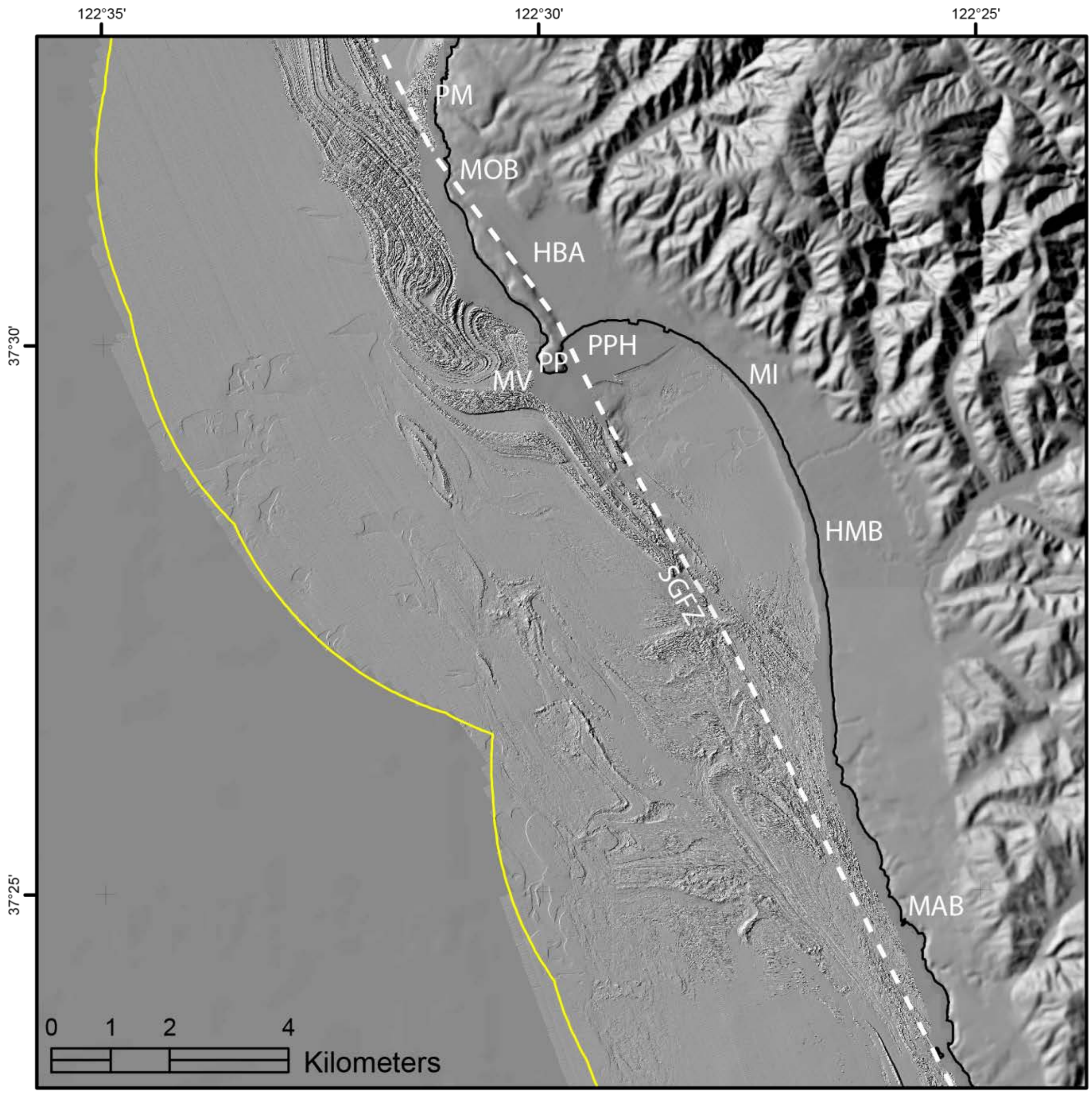

Figure 1–2. Coastal geography of Offshore of Half Moon Bay map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Gregorio Fault Zone (SGFZ). Other abbreviations: HBA, Half Moon Bay Airport; HMB, city of Half Moon Bay; MAB, Martins Beach; MOB, Moss Beach; MI, Miramar Beach; MV, Mavericks; PM, Point Montara; PP, Pillar Point; PPH, Pillar Point Harbor.

Chapter 2. Bathymetry and Backscatter-Intensity Maps of the Offshore of Half Moon Bay 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 Half Moon Bay 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 2007; the areas further offshore, by Fugro Pelagos in 2006 and 2007. 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 a 1-m-resolution image. 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 blueish greens to represent greater depths (note that the Offshore of Half Moon Bay 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 Half Moon Bay 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 Half Moon Bay 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 Half Moon Bay 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 light blues 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 views highlight the seafloor morphology in the Offshore of Half Moon Bay map area, which includes exposed outcrops of fractured bedrock and complex patterns of shallow depressions.

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 Half Moon Bay Map Area (Sheet 5)

By Guy R. Cochrane, Eleyne L. Phillips, and Mercedes D. Erdey

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 Game (CDFG), 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 Game, 2008). The CDFG 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 CDFG 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 Half Moon Bay 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 San Gregorio 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 Half Moon

Bay 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 Half Moon Bay 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 56.5 percent (71.6 km^2) of the map area: 15.1 percent (19.2 km^2) is in Depth Zone 2, and 41.4 percent (52.4 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 16.2 percent (20.5 km^2) of the map area: 8.5 percent (10.8 km^2) is in Depth Zone 2, and 7.7 percent (9.7 km^2) is in Depth Zone 3. Rock and boulder, rugose (rock outcrops and boulder fields having high surficial complexity) makes up 22.6 percent (28.6 km^2) of the map area: 18.9 percent (24.0 km^2) is in Depth Zone 2, and 3.6 percent (4.6 km^2) is in Depth Zone 3. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than surrounding seafloor) makes up 4.8 percent (6.0 km^2) of the map area: 0.6 percent (0.8 km^2) is in Depth Zone 2, and 4.1 percent (5.2 km^2) is in Depth Zone 3.

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 Half Moon Bay map area has extensive areas of Class III habitat composed of layered sedimentary rocks uplifted and folded by regional faulting. A sufficient number of video observations were made to complete accuracy assessment for all four sediment classes.

The classification accuracy of Classes I, III, and IV (67 percent, 61 percent, and 92 percent accurate, respectively; table 4–2) is determined by comparing the shipboard video observations and the classified map. The weaker (44 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 (90 percent for Class I, 94 percent for Class II, 95 percent for Class III, and 90 percent for Class IV).

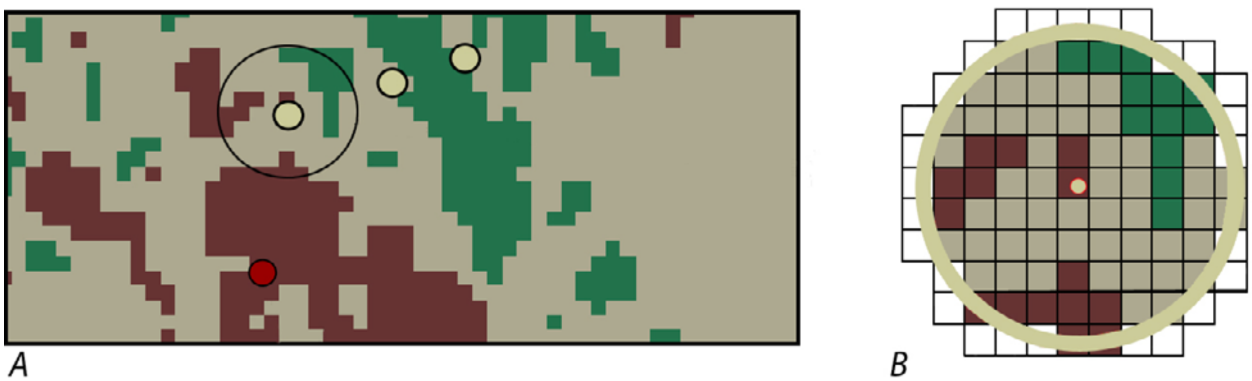

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted 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, and III for use in supervised classification and accuracy assessment in Offshore of Half Moon Bay 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			
mud	mud	low	
sand	mud	low	
sand	mud	trace	
sand	sand	low	
sand	sand	moderate	
sand	sand	trace	
sand	shell hash	low	
sand	shell hash	moderate	
shell hash	sand	moderate	
Class II			
boulders	cobbles	low	
boulders	sand	low	
cobbles	boulders	low	
cobbles	cobbles	low	
cobbles	cobbles	moderate	
cobbles	gravel	low	
cobbles	mud	moderate	
cobbles	rock	low	
cobbles	sand	low	
cobbles	sand	moderate	
cobbles	shell hash	low	
gravel	gravel	low	
gravel	sand	low	
gravel	shell hash	low	
mud	cobbles	low	
mud	rock	low	
rock	boulders	low	
rock	cobbles	low	
rock	mud	low	
rock	rock	low	
rock	sand	low	
rock	sand	trace	
sand	boulders	low	
sand	boulders	moderate	
sand	cobbles	low	
sand	cobbles	moderate	
sand	gravel	low	
sand	gravel	moderate	
sand	rock	low	
sand	rock	moderate	
shell hash	gravel	moderate	

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, and III for use in supervised classification and accuracy assessment in Offshore of Half Moon Bay map area.—*Continued*

[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 III			
boulders	boulders	high	
boulders	boulders	moderate	
boulders	cobbles	moderate	
boulders	rock	moderate	
boulders	sand	high	
boulders	sand	moderate	
cobbles	boulders	moderate	
cobbles	rock	moderate	
mud	rock	moderate	
rock	boulders	high	
rock	boulders	moderate	
rock	cobbles	high	
rock	cobbles	moderate	
rock	mud	moderate	
rock	rock	high	
rock	rock	moderate	
rock	sand	high	
rock	sand	moderate	
sand	rock	high	
Class IV			
sand	sand	moderate	
sand	shell hash	moderate	
shell hash	sand	moderate	
			megaripples
			oscillatory megaripples
			depression

Table 4–2. Accuracy-assessment statistics for seafloor-character-map classifications in Offshore of Half Moon Bay 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	335	67.0	90.5
II—Mixed smooth sediment and rock	328	43.7	94.2
III—Rock and boulder, rugose	392	61.3	94.9
IV—Medium- to coarse-grained sediment (in scour depressions)	31	91.6	90.3

Chapter 5. Ground-Truth Studies for the Offshore of Half Moon Bay Map Area (Sheet 6)

By Nadine E. Golden and Guy R. Cochrane

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

During the 2007 cruise, the USGS camera sled housed two standard-definition (640×480 pixel resolution) video cameras: one was forward looking, and the other was downward looking. During the 2008 cruise, a larger camera sled was used that housed two standard-definition (640×480 pixel resolution) video cameras (one forward looking and one downward looking), as well as a high-definition (1,080×1,920 pixel resolution) video camera and an 8-megapixel digital still camera. During this cruise, in addition to recording the seafloor characteristics, a digital still photograph was captured once every 30 seconds.

The camera-sled tracklines (shown by colored dots on the map on sheet 6) are sited in order to visually inspect areas representative of the full range of bottom hardness and rugosity in the map area. The video is fed in real time to the research vessel, where USGS and National Oceanic and Atmospheric Administration (NOAA) scientists record both the geologic and biologic character of the seafloor. While the camera is deployed, several different observations are recorded for a 10-second period once every

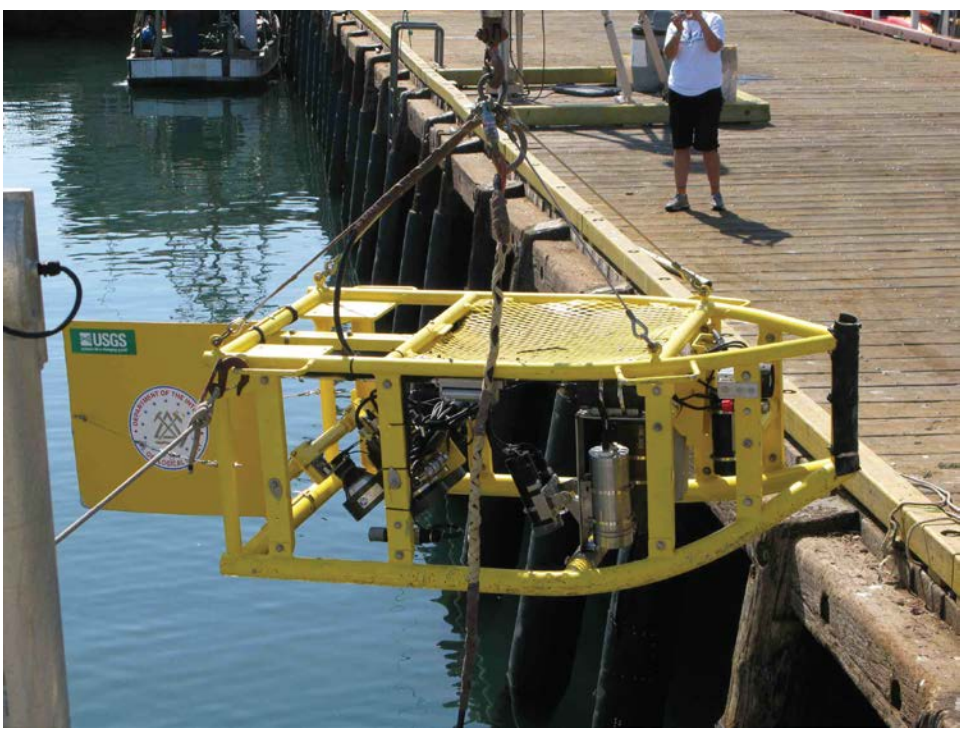

Figure 5–1. Photograph of camera sled used in USGS 2008 ground-truth survey.

minute, using the protocol of Anderson and others (2007). Observations of primary substrate, secondary substrate, slope, abiotic complexity, biotic complexity, and biotic cover are mandatory. Observations of key geologic features and the presence of key species also are made.

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

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

The ground-truth survey is designed to investigate areas that represent the full spectrum of high-resolution multibeam bathymetry and backscatter-intensity variation. Figure 5–2 shows that the Offshore of Half Moon Bay map area contains extensive areas of rocky habitat, mostly in the form of folded and differentially eroded sedimentary bedrock. Low areas formed where rock is more easily eroded; these areas often are covered with coarse sediment. Habitat grades into sand-dominated sediment that has bedforms indicative of bottom-current transport.

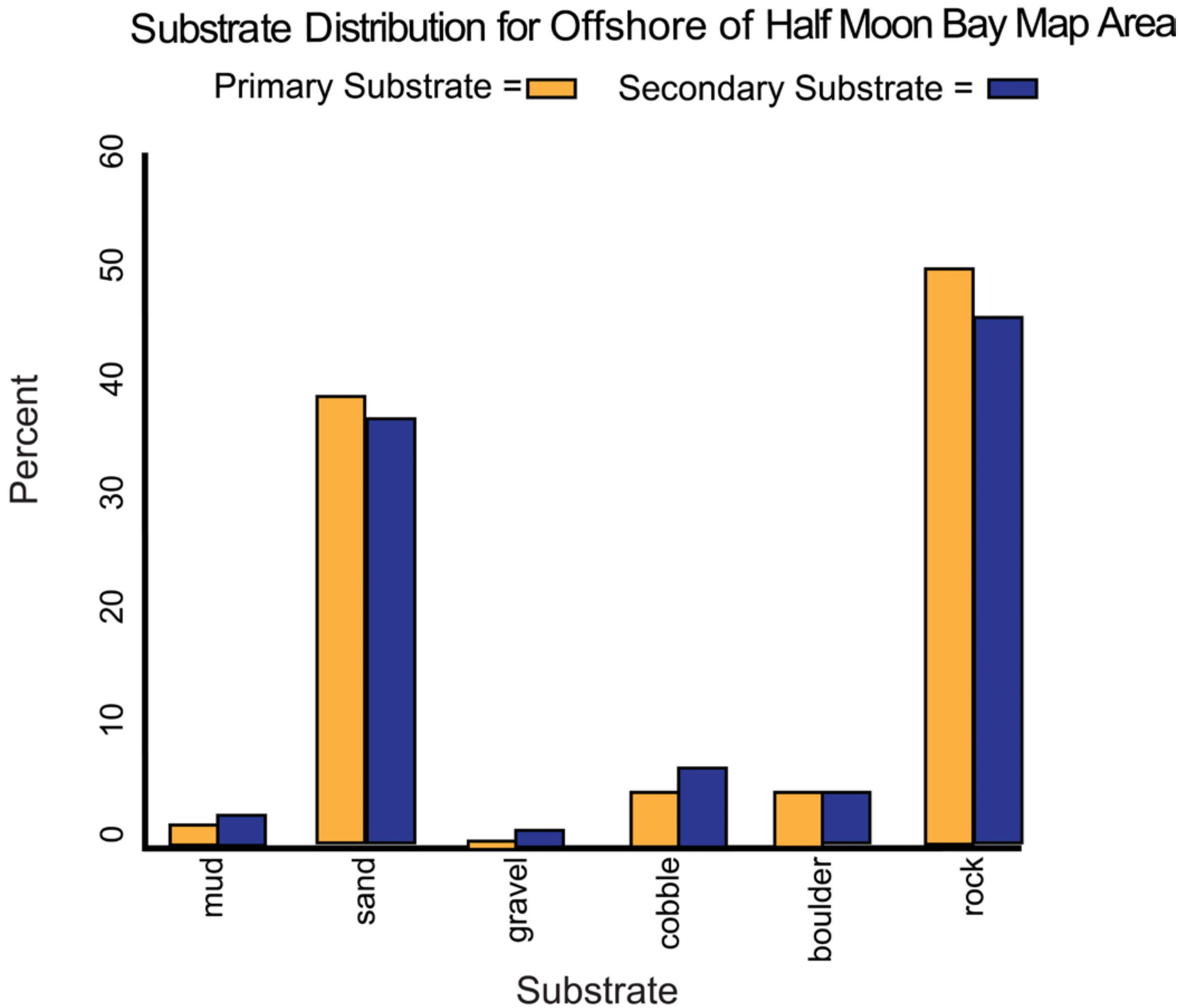

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Half Moon Bay map area.

Chapter 6. Potential Marine Benthic Habitats of the Offshore of Half Moon Bay 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 Half Moon Bay 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 Half Moon Bay 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 Half Moon Bay 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 Half Moon Bay 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 Half Moon Bay map area are 11 potential marine benthic habitat types, all located on the continental shelf ("Shelf" megahabitat), with two anthropogenic habitats found near the Pillar Point Harbor entrance. The meso- and macrohabitats include deformed sedimentary-outcrops, flat hard rock exposures, and rugose and fractured granitic rock, as well as dynamic features such as mobile sand sheets and associated scour depressions.

Most of the Offshore of Half Moon Bay map area is located on the relatively flat and eroded continental shelf. Backscatter data show that the map area is dominated by "soft" sediment; however, the highly deformed and differentially eroded bedrock outcrops and their seafloor relief present the most spectacular backscatter imagery in this map area. These differentially eroded bedrock areas form the local relief and rugosity that make promising potential habitats for rockfish (*Sebastes* spp.). Sediment transport is primarily to the southeast, and sedimentary processes, which are quite 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 in the northwestern and central parts of the map area.

Of the 126.8 km^2 in the map area, 56.25 km^2 (44.4 percent) is exposed hard bedrock, and 7.73 km^2 (6.1 percent) consists of sediment-covered bedrock, which is of the mixed hard-soft induration class. Soft, unconsolidated sediment covers a total of 70.5 km^2 (55.6 percent), and 62.77 km^2 (49.5 percent) consists of mobile sand sheets, ripple scour depressions, and gravels. Anthropogenic habitats cover 0.05 km^2 (0.04 percent) and are located in the vicinity of Pillar Point Harbor.

Chapter 7. Subsurface Geology and Structure of the Offshore of Half Moon Bay 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 Half Moon Bay 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 were collected in 2007 on USGS cruise F–2–07–NC. Single-channel seismic-reflection data were acquired using two different sources, the SIG 2Mille minisparker (figs. 1, 2, 4, 6, 9, 10) and the EdgeTech 512 chirp (fig. 7). The SIG minisparker 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). The EdgeTech 512 chirp subbottom-profiling system consists of a source transducer and an array of receiving hydrophones housed in a 500-lb fish towed at a depth of several meters below the sea surface. The swept-frequency chirp source signal was 500 to 4,500 Hz and 50 ms in length, and it was recorded by hydrophones located on the bottom of the fish.

Figure 3 on sheet 8 shows a seismic-reflection profile collected in 1997 on USGS cruise J–1–97–MB, using a 0.40- to 5-kHz Geopulse system. Power was supplied by a double-plate, 910-J sound source fired at 0.5-second intervals. As with the minisparker and chirp systems, data were digitally recorded and merged with GPS navigation data.

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.

Figure 8 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 Half Moon Bay map area straddles the right-lateral San Gregorio Fault system, an important structure in the distributed transform boundary between the North American and Pacific plates (see, for example, Dickinson and others, 2005). Regionally, this fault is part of a system that is present 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, extending onland at coastal promontories such as Pillar Point in this map area and also at Pescadero Point, 13 km south of the map area (see sheet 9; see also, Weber and Lajoie, 1980; Brabb and others, 1998). Offshore parts of this fault system are identified on seismic-reflection data 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.

In the Offshore of Half Moon Bay map area, the San Gregorio Fault forms a distributed, 2- to 5-km-wide shear zone that narrows northward and includes two main fault strands (see sheets 9, 10). The nearshore east strand (also known as the “Seal Cove Fault” or “Coastways Fault;” see figs. 3, 5 on sheet 8) forms a prominent bathymetric scarp (see sheets 1, 2). Weber (1990), Weber and others (1995), and Simpson and others (1997) suggested a dextral slip rate of 3.5 to 4.5 mm/yr for the onland part of the east strand on the basis of displacement of onshore marine-terrace shoreline angles and offset alluvial fan paleochannels. This estimated rate represents a represents a minimum for the San Gregorio Fault system because the offshore west strand (also known as the “Frijoles Fault”; see figs. 1, 2, 3, 4, 5, 6, 7, 8, 10 on sheet 8) also is active. Cumulative lateral slip on this fault zone is thought to range from 4 to 10 mm/yr in this area (U.S. Geological Survey and California Geological Survey, 2010).

The Offshore of Half Moon Bay map area also notably lies along southwestern flank of 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 (see, for example, Zoback and others, 1999). Rates of uplift of marine terraces in and near the map area of as much as 0.44 mm/yr confirm that this regional uplift includes the coastal zone (Weber and others, 1995).

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 Offshore of Half Moon Bay map area is notably devoid of seismicity during this time period. 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).

Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Half Moon Bay map area, herein considered part of the Pacifica-Pescadero shelf. This shelf (see Maps A, B on sheet 9), which is relatively flat (less than 0.6°) and shallow (55 m or less), 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 Half Moon Bay 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, 7, 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 Half Moon Bay 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, E) 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, 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 Half Moon Bay map area ranges from 0 to 13 m (Map B on sheet 9), and the depth to the base of this unit ranges from less than 10 to 62 m (Map A on sheet 9). The most rapid changes in thickness are in the northern 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 2.5 m, and the total sediment volume is 309×10^6 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 Half Moon Bay map area).

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

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

Table 7–1. Area, sediment-thickness, and sediment-volume data for California's State Waters in Bolinas to Pescadero region (domains 1–5), as well as in Offshore of Half Moon Bay 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 Half Moon Bay map area			
Offshore of Half Moon Bay map area	123	2.5	309

Chapter 8. Geologic and Geomorphic Map of the Offshore of Half Moon Bay Map Area (Sheet 10)

By H. Gary Greene, Michael W. Manson, Charles A. Endris, and Samuel Y. Johnson

Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Half Moon Bay 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 Half Moon Bay map area is shallow (less than about 55 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 and sedimentation as sea level rose about 125 to 130 m during 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 Half Moon Bay map area is now an open-ocean shelf that is subjected to full, and sometimes severe, wave energy and strong currents.

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 only as a nearshore bar (about 10 m water depth) just south of the Pillar Point Harbor jetty. Unit Qmss, which typically is mapped as erosional lags in scour depressions (see, for example, Cacchione and others, 1984), is more extensive and distributed, the largest concentrations found at water depths of 30 to 55 m offshore of Pillar Point, as well as in the nearshore (at depths of 5 to 15 m) south of Pillar Point Harbor and north-northwest of Pillar Point. 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 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 upper Miocene and Pliocene Purisima Formation (unit Tp), the Cretaceous granitic rocks of Montara Mountain (unit Kgr), and undifferentiated sedimentary rocks of the undivided bedrock unit of Cretaceous and (or) Tertiary age (TKu). These units are delineated by extending outcrops and trends from mapped onshore geology and also by their distinctive surface textures as revealed by high-resolution bathymetry (see sheets 1, 2). 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. The Offshore of Half Moon Bay map area contains artificial fill (unit af) only inside Pillar Point Harbor.

Areas where shelf sediments form thin (2.5 m or less) veneers over low-relief rocks of the undivided Cretaceous and (or) Tertiary bedrock unit or the Purisima Formation (upper Miocene and Pliocene) are mapped as units Qms/TKu and Qms/Tp, 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 55 km south of the map area. The relative proportions of all offshore map units are shown in table 8–1.

The Offshore of Half Moon Bay map area lies about 12 km southwest of the San Andreas Fault, the dominant structure in the distributed, right-lateral, transform boundary between the North American and Pacific plates. The map area straddles the right-lateral San Gregorio Fault system, a prominent structure west of the San Andreas Fault in the broader San Andreas Fault system. The San Gregorio Fault system extends for about 400 km from Point Conception on the south to Bolinas and Point Reyes on the north (Dickinson and others, 2005), predominantly in the offshore but also onshore at coastal promontories such as Pillar Point in the map area and also at Pescadero Point, about 15 km south of the map area (see Map E on sheet 9).

In the Offshore of Half Moon Bay map area, the San Gregorio Fault system forms a distributed shear zone about 2 to 4.5 km wide that includes two main diverging fault strands (fig. 1 on sheet 10). The east strand (also known as the Seal Cove Fault or Coastways Fault), which roughly parallels the shoreline, extends onshore for about 3 km at Pillar Point, locally forming the boundary between outcrops of Cretaceous granitic rocks to the east and the Purisima Formation to the west. The west strand (also known as the Frijoles Fault), which lies entirely offshore, forms a boundary between the Purisima Formation on the east and undivided Cretaceous and (or) Tertiary rocks of the Pigeon Point block (McCulloch, 1987) (fig. 1 on sheet 10) on the west. The Pigeon Point block is a northwest-trending bedrock ridge that extends offshore of Pescadero for about 30 km and forms the northwest boundary of the Outer Santa Cruz Basin.

Table 8–1. Areas and relative proportions of offshore geologic map units in Offshore of Half Moon Bay map area.

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine sedimentary units			
Qms	46,167,829	46.17	35.53
Qmsc	688,821	0.69	0.53
Qmss	5,906,449	5.91	4.55
Total, sedimentary units	52,763,099	52.76	40.61
Marine bedrock and (or) shallow bedrock units			
Qms/Tp	20,255,887	20.26	15.59
Qms/TKu	1,579,076	1.58	1.22
Tp	54,214,557	54.21	41.72
TKu	292,980	0.29	0.23
Kgr	830,518	0.83	0.64
Total, bedrock units	77,173,018	77.17	59.39
Total, Offshore of Half Moon Bay map area	129,936,117	129.94	100.00

Bathymetric data (see sheets 1, 2) and seismic-reflection profiles (see sheet 8) reveal that the offshore exposures of the Purisima Formation between the east and west strands of the San Gregorio Fault Zone have been spectacularly folded, faulted, and rotated by strike-slip motion and drag along the faults. Cumulative lateral slip on the San Gregorio Fault system is thought to range from 4 to 10 mm/yr in this area (U.S. Geological Survey and California Geological Survey, 2010).

The entire map area lies along strike with the young, high topography of the Santa Cruz Mountains and Coast Ranges (see sheet 9). This regional uplift has been linked to a northwest-transpressive bend in the San Andreas Fault (see, for example, Zoback and others, 1999). Rates of uplift of marine terraces of as much as 0.44 mm/yr near Año Nuevo, 30 km south of the map area, confirms that regional uplift is ongoing and that it includes the coastal zone (Weber, 1990).

DESCRIPTION OF MAP UNITS

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

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

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 1º) surface in water depths typically less than about 20 m; recognized primarily on basis of variable and mottled backscatter

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. Stippled areas (composite unit Qms/Tp) indicate where thin sheets of Qms overlie unit

TKu **Bedrock, undivided (Tertiary and (or) Cretaceous)**—Stippled areas (composite unit Qms/TKu) indicate where thin sheets of Qms overlie unit

Kgr **Granitic rocks of Montara Mountain (Cretaceous)**—Medium-crystalline to coarsely crystalline, foliated granitic rock; largely quartz diorite with some granite

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. Locations of some faults from California Geological Survey (1976, 1982, 2002b)]

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

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

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

Qc **Stream-channel deposits (late Holocene)**—Fluvial deposits within active, natural stream channels

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

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

Qt2 **Stream-terrace deposits (Holocene)**—Relatively smooth, undissected terraces less than 8 to 10 m above active channel; younger than unit Qt1

Qt1 **Stream-terrace deposits (Holocene)**—Relatively smooth, undissected terraces less than 8 to 10 m above active channel; older than unit Qt2

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

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

Qof2 **Older alluvial fan deposits, undivided (Holocene and late Pleistocene)**—Mapped in small valleys where separate fan, basin, and terrace units could not be delineated at 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

Qof1 **Older alluvial fan deposits (late Pleistocene)**—Alluvial fans; late Pleistocene age is indicated by degree of dissection or soil development greater than what is present on Holocene fans

Qot **Older stream-terrace deposits (late Pleistocene)**—Relatively flat, slightly dissected stream terraces; late Pleistocene age is indicated by degree of soil development and height of terrace above flood level

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 (Qmt4) to oldest (Qmt1)

Qmt4 **Marine-terrace deposits (Pleistocene)**—Sand and gravel, deposited on uplifted marine-abrasion platforms along coast

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

Tp **Purisima Formation, undivided (Pliocene and late Miocene)**—Medium-grained to very fine-grained, poorly indurated to friable sandstone, siltstone, and claystone, with conglomerate lenses and a few beds of white volcanic ash

Tptu **Tunitas Sandstone Member (Pliocene)**—Fine-grained sandstone, siltstone, and mudstone; some porcelaneous shale and mudstone, chert, silty mudstone, and volcanic ash

Tpl **Lobitos Mudstone Member (Pliocene)**—Massive silty mudstone

Tpsg **San Gregorio Sandstone Member (Pliocene)—**Fine- to coarse-grained sandstone that has calcareous concretions

Tpp **Pomponio Mudstone Member (Pliocene)—**Porcelaneous shale and mudstone; in places, rhythmically bedded with alternating layers of nonsiliceous mudstone

Tpt **Tahana Member (Pliocene and late Miocene)—**Medium-grained to very fine-grained lithic sandstone and siltstone, interbedded with some silty mudstone, tuffaceous sandstone, and pebble conglomerate

Tm **Monterey Formation (Miocene)**—Porcelaneous shale with chert, porcelaneous mudstone, impure diatomite, and calcareous claystone, as well as small amounts of siltstone and sandstone near base

Tlo **Lompico Sandstone (Miocene)**—Fine- to coarse-grained, well-cemented arkosic sandstone

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**—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

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

m **Marble and hornfels blocks (Paleozoic?)—**Finely crystalline marble, graphitic marble, and quartz-mica hornfels

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 Brian Edwards and Michael Fisher (both 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.

References Cited

Ainley, D.B., and Hyrenbach, K.D., 2010, Top-down and bottom-up factors affecting seabird population trends in the California current system (1985-2006): Progress in Oceanography, v. 84, p. 242–254.

Anderson, T.J., Cochrane, G.R., Roberts, D.A., Chezar, H., and Hatcher, G., 2007, A rapid method to characterize seabed habitats and associated macro-organisms, *in* Todd, B.J., and Greene, H.G., eds., Mapping the seafloor for habitat characterization: Geological Association of Canada Special Paper 47, p. 71–79.

Barnard, P.L., Eshelman, J., Erikson, L., and Hanes, D.M., 2007, Coastal processes study at Ocean Beach, San Francisco, CA—Summary of data collection 2004–2006: U.S. Geological Survey Open-File Report 2007–1217, 165 p., available at http://pubs.usgs.gov/of/2007/1217/.

Bolt, B.A., 1968, The focus of the 1906 California earthquake: Bulletin of the Seismological Society of America, v. 58, p. 457–471.

Brabb, E.E., Graymer, R.W., and Jones, D.L., 1998, Geology of the onshore part of San Mateo County, California—A digital database: U.S. Geological Survey Open-File Report 98–137, scale 1:62,500, available at http://pubs.usgs.gov/of/1998/of98-137/.

Briggs, J.C., 1974, Marine zoogeography: New York, McGraw-Hill, 480 p.

Bruns, T.R., Cooper, A.K., Carlson, P.R., and McCulloch, D.S., 2002, Structure of the submerged San Andreas and San Gregorio Fault zones in the Gulf of the Farallones off San Francisco, California, from high-resolution seismic-reflection data, *in* Parsons, T., ed., Crustal structure of the coastal and marine San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1658, p. 77–117, available at http://pubs.usgs.gov/pp/1658/.

Cacchione, D.A., Drake, D.E., Grant, W.D., and Tate, G.B., 1984, Rippled scour depressions of the inner continental shelf off central California: Journal of Sedimentary Petrology, v. 54, p. 1,280–1,291.

Calambokidis, J., and Barlow, J., 2004, Abundance of blue and humpback whales in the eastern North Pacific estimated by capture-recapture and line-transect methods: Marine Mammal Science, v. 20, p. 63–85.

California Department of Fish and Game, 2008, California Marine Life Protection Act master plan for marine protected areas—Revised draft: California Department of Fish and Game, accessed April 5, 2011, at http://www.dfg.ca.gov/mlpa/masterplan.asp.

California Geological Survey, 1976, Alquist-Priolo earthquake fault zone map of Half Moon Bay quadrangle: California Geological Survey, State of California Special Studies Zone Map, scale 1:24,000, available at http://www.quake.ca.gov/gmaps/WH/regulatorymaps.htm.

California Geological Survey, 1982, Alquist-Priolo earthquake fault zone map of Montara Mountain quadrangle: California Geological Survey, State of California Special Studies Zone Map, scale 1:24,000, available at http://www.quake.ca.gov/gmaps/WH/regulatorymaps.htm.

California Geological Survey, 2002a, California geomorphic provinces: California Geologic Survey Note 36, 4 p.

California Geological Survey, 2002b, Fault evaluation reports prepared under the Alquist-Priolo Earthquake Fault Zoning Act—Region 1, central California: California Geological Survey, CGS CD 2002–01, available at http://www.conservation.ca.gov/cgs/rghm/ap/ap_fer_cd/Pages/index.aspx.

Catuneanu, O., 2006, Principles of sequence stratigraphy: Amsterdam, Elsevier, 375 p.

Childs, J.R., Hart, P., Bruns, T.R., Marlow, M.S., and Sliter, R., 2000, High-resolution marine seismic reflection data from the San Francisco Bay area: U.S. Geological Survey Open-File Report 00–494, available at http://pubs.usgs.gov/of/2000/0494/.

Cochrane, G.R., 2008, Video-supervised classification of sonar data for mapping seafloor habitat, *in* Reynolds, J.R., and Greene, H.G., eds., Marine habitat mapping technology for Alaska: Fairbanks, University of Alaska, Alaska Sea Grant College Program, p. 185–194, available at http://doc.nprb.org/

web/research/research%20pubs/615_habitat_mapping_workshop/Individual%20Chapters%20High-Res/Ch13%20Cochrane.pdf.

Cochrane, G.R., Conrad, J.E., Reid, J.A., Fangman, S., and Golden, N., 2005, The nearshore benthic habitat GIS for the Channel Islands National Marine Sanctuary and southern California state fisheries reserves, vol. II: U.S. Geological Survey Open-File Report 2005–1170, available at http://pubs.usgs.gov/of/2005/1170/.

Cochrane, G.R., Nasby, N.M., Reid, J.A., Waltenberger, B., and Lee, K.M., 2003, Nearshore benthic habitat GIS for the Channel Islands National Marine Sanctuary and southern California state fisheries reserves, vol. I: U.S. Geological Survey Open-File Report 03–85, available at http://pubs.usgs.gov/of/2003/0085/.

Collins, C.A., Garfield, N., Rago, T.A., Rischmiller, F.W., and Carter, E., 2000, Mean structure of the inshore counter-current and California undercurrent off Point Sur, California: Deep-Sea Research II, v. 47, p. 765–782.

Cooper, A.K., 1973, Structure of the continental shelf west of San Francisco, California: U.S. Geological Survey Open-File Report 73–48, 65 p.

Davis, A.C.D., Kvitek, R.G., Mueller, C.B.A., Young, M.A., Storlazzi, C.D., and Phillips, E.L., 2013, Distribution and abundance of rippled scour depressions along the California coast: Continental Shelf Research, v. 69, p. 88–100, doi:10.1016/j.csr.2013.09.010.

Dawson, M.N., Waples, R.S., and Bernardi, G., 2006, Phylogeography, *in* Allen, L.G., Pondella, D.J., II, and Horn, M.H., eds, The ecology of marine fishes, California and adjacent waters: Berkeley, University of California Press, 660 p.

Dickinson, W.R., 2004, Evolution of the North American cordillera: Annual Reviews of Earth and Planetary Sciences, v. 32, p. 13–45.

Dickinson, W.R., Ducea, M., Rosenberg, L.I., Greene, H.G., Graham, S.A., Clark, J.C., Weber, G.E., Kidder, S., Ernst, W.G., and Brabb, E.E., 2005, Net dextral slip, Neogene San Gregorio–Hosgri fault zone, coastal California—Geologic evidence and tectonic implications: Geological Society of America Special Paper 391, 43 p.

Fader, G.B.J., 1997, The effects of shallow gas on seismic reflection profiles, *in* Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S., and Stravers, J.A., eds., Glaciated continental margins, an atlas of acoustic images: London, Chapman and Hall, p. 29–30.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record—Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Science, v. 342, p. 637–642.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., and Chappell, J., 1998, Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites: Earth and Planetary Science Letters, v. 163, p. 327–342.

Goff, J.A., Mayer, L., Traykovski, P., Buynevich, I., Wilkins, R., Raymond, R., Glang, G., Evans, R.L., Olson, H., and Jenkins, C., 2005, Detailed investigation of sorted bedforms, or “rippled scour depressions,” within the Martha’s Vineyard Coastal Observatory, Massachusetts: Continental Shelf Research, v. 25, p. 461–484.

Gornitz, V., 2009, Sea level change, post-glacial, *in* Gornitz, V., ed., Encyclopedia of paleoclimatology and ancient environments: Springer, Encyclopedia of Earth Sciences Series, p. 887–893.

Greene, H.G., Bizzarro, J.J., O’Connell, V.M., and Brylinsky, C.K., 2007, Construction of digital potential marine benthic habitat maps using a coded classification scheme and its application, *in* Todd, B.J., and Greene, H.G., eds., Mapping the seafloor for habitat characterization: Geological Association of Canada Special Paper 47, p. 141–155.

Greene, H.G., Bizzarro, J.J., Tilden, J.E., Lopez, H.L., and Erdey, M.D., 2005, The benefits and pitfalls of geographic information systems in marine benthic habitat mapping, *in* Wright, D.J., and Scholz, A.J., eds., Place matters: Portland, Oregon State University Press, p. 34–46.

Greene, H.G., Yoklavich, M.M., Starr, R.M., O'Connell, V.M., Wakefield, W.W., Sullivan, D.E., McRea, J.E., and Cailliet, G.M., 1999, A classification scheme for deep seafloor habitats: Oceanologica Acta, v. 22, p. 663–678.

Griggs, G., Patsch, K., and Savoy, L., 2005, Living with the changing California Coast: Berkeley, University of California Press, 540 p.

Hallenbeck, T.R., Kvitek, R.G., and Lindholm, J., 2012, Rippled scour depressions add ecologically significant heterogeneity to soft-bottom habitats on the continental shelf: Marine Ecology Progress Series, v. 468, p. 119–133, doi:10.3354/meps09948.

Hapke, C.J., Reid, D., Richmond, B.B., Ruggiero, P., and List, J., 2006, National assessment of shoreline change, part 3—Historical shoreline change and associated coastal land loss along sandy shorelines of the California coast: U.S. Geological Survey Open-File Report 2006–1219, 72 p., available at http://pubs.usgs.gov/of/2006/1219/.

Inman, D.L., and Jenkins, D.A., 1999, Climate change and the episodicity of sediment flux of small California rivers: Journal of Geology, v. 107, p. 251–270.

Koehl, M.A.R., and Wainwright, S.A., 1977, Mechanical adaptations of a giant kelp: Limnology and Oceanography, v. 22, p. 1,067–1,071.

Kvitek, R., Bretz, C., Cochrane, G., and Greene, H.G., 2006, Final report, Statewide Marine Mapping Planning Workshop, December 12–13, 2005, Seaside, Calif.: California State University, Monterey Bay, 108 p., available at http://euclase.csumb.edu/DATA_DOWNLOAD/StrategicMapgWrkshp05/MappingWorkshop12_1213/Final_Report/CA%20Habitat%20Mapping%20Rpt.pdf.

Kvitek, R.G., Phillips, E.L., and Dartnell, P., 2012, Colored shaded-relief bathymetry, Hueneme Canyon and vicinity, California, *sheet 1 in* Johnson, S.Y., Dartnell, P., Cochrane, G.R., Golden, N.E., Phillips, E.L., Ritchie, A.C., Kvitek, R.G., Greene, H.G., Krigsman, L.M., Endris, C.A., Clahan, K.B., Sliter, R.W., Wong, F.L., Yoklavich, M.M., and Normark, W.R. (S.Y. Johnson, ed.), California State Waters Map Series—Hueneme Canyon and vicinity, California: U.S. Geological Survey Scientific Investigations Map 3225, pamphlet 41 p., 12 sheets, available at http://pubs.usgs.gov/sim/3225/.

Lajoie, K.R., 1986, Coastal tectonics, *in* National Research Council Geophysics Study Committee, ed., Active tectonics: Washington, D.C., National Academy Press, p. 95–124.

Lajoie, K.R., Ponti, D.J., Powell, C.L., II, Mathieson, S.A., and Sarna-Wojcicki, A.M., 1991, Emergent marine strandlines and associated sediments, coastal California—A record of Quaternary sea-level fluctuations, vertical tectonic movements, climatic changes, and coastal processes, *in* Morrison, R.B., ed., The Geology of North America, Quaternary nonglacial geology—Conterminous U.S.: Geological Society of America, Decade of North American Geology, v. K–2, p. 190–213.

Lambeck, K., and Chappell, J., 2001, Sea level change through the last glacial cycle: Science, v. 292, p. 679–686, doi:10.1126/science.1059549.

Lambeck, K., Yokoyama, Y., and Purcell, T., 2002, Into and out of the Last Glacial Maximum—Sea-level change during oxygen isotope stages 3 and 2: Quaternary Science Reviews, v. 21, p. 343–360.

Lomax, A., 2005, A reanalysis of the hypocentral location and related observations for the Great 1906 California earthquake: Bulletin of the Seismological Society of America, v. 95, p. 861–877, doi:10.1785/0120040141.

Lynn, R.J., and Simpson, J.J., 1987, The California Current system—The seasonal variability of its physical characteristics: Journal of Geophysical Research, v. 92, p. 12,947–12,966.

Madden, C.J., Goodin, K.L., Allee, R., Finkbeiner, M., and Bamford, D.E., 2008, Draft Coastal and Marine Ecological Classification Standard: National Oceanic and Atmospheric Administration (NOAA) and NatureServe, v. III, 77 p.

McCulloch, D.S., 1987, Regional geology and hydrocarbon potential of offshore central California, *in* Scholl, D.W., Grantz, A., and Vedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 353–401.

McGowan, J.A., Cayan, D.R., and Korman, L.M., 1998, Climate-ocean variability and ecosystem response in the Northeast Pacific: Science, v. 281, p. 210–217.

Miller, K.A., and Estes, J.A., 1989, Western range extension for Nereocystis luetkeana in the North Pacific Ocean: Botanica Marina, v. 32, p. 535–538.

Mitchum, R.M., Jr., Vail, P.R., and Sangree, J.B., 1977, Seismic stratigraphy and global changes of sea level, part 6—Stratigraphic interpretation of seismic reflection patterns in depositional sequences, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: Tulsa, Okla., American Association of Petroleum Geologists, p. 117–133.

Murray, A.B., and Thieler, 2004, A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and "rippled scour depressions:" Continental Shelf Research, v. 24, no. 3, p. 295–315.

Northern California Earthquake Data Center, 2014, Northern California earthquake catalog: Northern California Earthquake Data Center database, accessed April 5, 2014, at http://www.ncedc.org/ncsn/.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, p. 3,322–3,337, doi:10.1016/j.quascirev.2006.04.010.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p., available at http://pubs.usgs.gov/of/2008/1128/.

Phillips, E.L., Storlazzi, C.D., Dartnell, P., and Edwards, B.D., 2007, Exploring rippled scour depressions offshore Huntington Beach, CA: Coastal Sediments 2007, v. 3, p. 1,851–1,864.

Reid, J.A., Reid, J.M., Jenkins, C.J., Zimmerman, M., Williams, S.J., and Field, M.E., 2006, usSEABED—Pacific Coast (California, Oregon, Washington) offshore surficial-sediment data release: U.S. Geological Survey Data Series 182, available at http://pubs.usgs.gov/ds/2006/182/.

Ryan, H.F., Parsons, T., and Sliter, R.W., 2008, Vertical tectonic deformation associated with the San Andreas Fault Zone offshore of San Francisco, California: Tectonophysics, v. 429, p. 209–224, doi:10.1016/j.tecto.2008.06.011.

Simpson, G.D., Thompson, S.C., Noller, J.S., and Lettis, W.R., 1997, The northern San Gregorio fault zone—Evidence for the timing of late Holocene earthquakes near Seal Cove, California: Bulletin of the Seismological Society of America, v. 87, p. 1,158–1,170.

Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdana, Z.A., Finlayson, M., Halpern, B.S., Jorge, M.A., Lombana, A., Lourie, S.A., Martin, K.D., McManus, E., Molnar, J., Recchia, C.A., and Robertson, J., 2007, Marine ecoregions of the world—A bioregionalization of coastal and shelf areas: BioScience, v. 57, p. 573–583.

Stanford, J.D., Hemingway, R., Rohling, E.J., Challenor, P.G., Medina-Elizalde, M., and Lester, A.J., 2011, Sea-level probability for the last deglaciation—A statistical analysis of far-field records: Global and Planetary Change, v. 79, p. 193–203, doi:10.1016/j.gloplacha.2010.11.002.

Stephens, J.S., Larson, R.J., and Pondella, D.J., II, 2006, Rocky reefs and kelp beds, *in* Allen, L.G., Pondella, D.J., II, and Horn, M.H., eds., The ecology of marine fishes, California and adjacent waters: Berkeley, University of California Press, 660 p.

Storlazzi, C.D., Fregoso, T.A., Golden, N.E., and Finlayson, D.P., 2011, Sediment dynamics and the burial and exhumation of bedrock reefs along on emergent coastline as elucidated by repetitive sonar surveys, northern Monterey Bay, CA: Marine Geology, v. 289, p. 46–59, doi:10.1016/j.margeo.2011.09.010.

Tissot, B.N., Yoklavich, M.M., Love, M.S., York, K., and Amend, M., 2006, Benthic invertebrates that form habitat on deep banks off southern California, with special reference to deep sea coral: Fishery Bulletin, v. 104, p. 167–181.

Trembanis, A.C., and Hume, T.M., 2011, Sorted bedforms on the inner shelf off northeastern New Zealand—Spatiotemporal relationships and potential paleo-environmental implications: Geo-Marine Letters, v. 31, p. 203–214.

U.S. Geological Survey, 2009, National Archive of Marine Seismic Surveys: U.S. Geological Survey database, accessed April 5, 2011, at http://walrus.wr.usgs.gov/NAMSS/.

U.S. Geological Survey and California Geological Survey, 2010, Quaternary fault and fold database of the United States: U.S. Geological Survey database, accessed April 5, 2014, at http://earthquake.usgs.gov/hazards/qfaults/.

Weber, G.E., 1990, Late Pleistocene slip rates on the San Gregorio fault zone at Point Año Nuevo, San Mateo County, California, *in* Greene, H.G., Weber, G.E., Wright, T.L., and Garrison, R.E., eds., Geology and tectonics of the central California coast region—San Francisco to Monterey: American Association of Petroleum Geologists, Pacific Section, volume and guidebook, v. 67, p. 193–204.

Weber, G.E., and Lajoie, K.R., 1980, Map of Quaternary faulting along the San Gregorio fault zone, San Mateo and Santa Cruz Counties, California: U.S. Geological Survey Open-File Report 80–907, scale 1:24,000.

Weber, G.E., Nolan, J.M., and Zinn, E.N., 1995, Determination of late Pleistocene-Holocene slip rates along the San Gregorio fault zone, San Mateo and Santa Cruz Counties, California—Final Technical Report: National Earthquake Hazard Reduction Program, Final Technical Report, Contract No. 1434–93–G–2336, 70 p., 4 sheets.

Weber, K.M., List, J.H., and Morgan, K.L.M., 2005, An operational mean high water datum for determination of shoreline position from topographic lidar data: U.S. Geological Survey Open-File Report 2005–1027, available at http://pubs.usgs.gov/of/2005/1027/.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377–392.

Witter, R.C., Knudsen, K.L., Sowers, J.M., Wentworth, C.M., Koehler, R.D., Randolph, C.E., Brooks, S.K., and Gans, K.D., 2006, Maps of Quaternary deposits and liquefaction susceptibility in the central San Francisco Bay region, California: U.S. Geological Survey Open-File Report 2006–1037, scale 1:24,000, available at http://pubs.usgs.gov/of/2006/1037/.

Wong, F.L., Phillips, E.L., Johnson, S.Y., and Sliter, R.W., 2012, Modeling of depth to base of Last Glacial Maximum and seafloor sediment thickness for the California State Waters Map Series, eastern Santa Barbara Channel, California: U.S. Geological Survey Open-File Report 2012–1161, 16 p., available at http://pubs.usgs.gov/of/2012/1161/.

Zoback, M.L., Jachens, R.C., and Olson, J.A., 1999, Abrupt along-strike change in tectonic style—San Andreas fault zone, San Francisco Peninsula: Journal of Geophysical Research, v. 104 (B5), p. 10,719–10,742.