California State Waters Map Series—Offshore of Monterey, California

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(Samuel Y. Johnson and Susan A. Cochran, editors)

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Preface

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

The CSMP approach is to create highly detailed seafloor maps through collection, integration, interpretation, and visualization of swath sonar bathymetric 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 marine benthic habitats, and illustrate both the surficial seafloor geology and shallow 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 limit of California's State Waters. Unfortunately, surveying the zone from MHHW out to 10-m water depth is not consistently possible using ship-based surveying methods, owing to sea state (for example, waves, wind, or currents), kelp coverage, and shallow rock outcrops. Accordingly, some of the maps presented in this series commonly do not cover the zone from the shore out to 10-m depth; these "no data" zones appear pale gray on most maps.

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

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raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed March 5, 2014). Web services, which consist of standard implementations of ArcGIS REST Service and OGC GIS Web Service (WMS), also are available for all published GIS data. All CSMP web services were created using an ArcGIS service definition file, resulting in data layers that are symbolized as shown on the associated map sheets. Both the ArcGIS REST Service and OGC WMS Service include all the individual GIS layers for each map-area publication. Data layers are bundled together in a map-area web service; however, each layer can be symbolized and accessed individually after the web service is ingested into a desktop application or web map. CSMP web services enable users to download and view CSMP data, as well as to easily add CSMP data to their own workflows, using any browser-enabled, standalone or mobile device.

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

Chapter 1. Introduction

By Samuel Y. Johnson

Regional Setting

The map area offshore of the Monterey peninsula, which is referred to herein as the “Offshore of Monterey” map area (figs. 1–1, 1–2), is located on the Pacific Coast in central California, 120 km south of San Francisco. The map area includes the seafloor in the southern part of Monterey Bay, as well as west and south of Monterey peninsula. Note that the California’s State Waters limit, which generally is 3 nautical miles [5.6 km] from shore, extends farther offshore (as much as 12 nautical miles) between Santa Cruz and Monterey, so that it encompasses all of Monterey Bay (see figs. 1–1, 1–2).

Incorporated cities in the map area (approximate populations given in parentheses) include Seaside (33,025), Monterey (21,780), Marina (20,730), Pacific Grove (15,504), Carmel-by-the-Sea (3,700), and Sand City (334). The local economy receives significant resources from tourism, as well as from the Federal Government. Tourist attractions include the Monterey Bay Aquarium, Cannery Row, Fisherman’s Wharf, and the many golf courses near Pebble Beach, and the area serves as a gateway to the spectacular scenery and outdoor activities along the Big Sur coast to the south. Federal facilities include the Army’s Defense Language Institute, the Naval Postgraduate School, and the Fleet Numerical Meteorology and Oceanography Center (operated by the Navy), one of the world’s leading numerical weather prediction centers. In 1994, the large (8.1 km^2) Fort Ord army base, located between Seaside and Marina, was closed. Much of former army base land now makes up the Fort Ord National Monument, managed by the U.S. Bureau of Land Management as part of the National Landscape Conservation System. In addition, part of the old Fort Ord is now occupied by California State University, Monterey Bay, which opened in 1994 and had an enrollment of 7,102 in 2015.

The coastal zone in the Offshore of Monterey map area is characterized by two distinct physiographies (Griggs and others, 2005). From Marina to Monterey, in the northeastern part of the map area, a wide belt of sand dunes, which reaches elevations of 30 to 40 m and extends inland as far as 8 km, backs wide, sandy beaches (Cooper, 1967). The Salinas River supplies the sand for the beaches and dunes. Nearshore sediment transport is primarily to the south, in the southern Monterey littoral cell. Hapke and others (2006) reported that beaches on this coast typically have long-term (1862–2002) erosion rates of about 0.4 to 1.0 m/yr; the short-term (1952–2002) rates typically range from about 1.0 to 1.8 m/yr. They further reported a maximum long-term erosion rate of 1.3 m/yr on Indian Head Beach, near Marina, and a maximum short-term rate of 2.4 m/yr at Seaside (fig. 1–2).

Coastal relief is very different along the Monterey peninsula, in the southwestern part of the map area. The peninsula, which lies at the north end of the rugged Santa Lucia Range (fig. 1–1), is characterized largely by low (less than 15 m) marine terraces that formed mostly on hard and relatively stable granitic bedrock (Hapke and Reid, 2007). The 2-km-long Carmel Beach in Carmel-by-the-Sea is the longest continuous beach in this area; bedrock points and small pocket beaches characterize most of the rest of the Monterey peninsula. The Carmel River littoral cell extends along the coast from Point Pinos to Point Lobos (just south of the map area; see fig. 1–1), including Carmel Beach; sediment transport is primarily to the south. Carmel Beach has an overall long-term (1862–2002) accretionary trend; however, the southern part of the beach has a short-term (1952–2002) erosion rate of 1.7 m/yr (Hapke and others, 2006).

The granitic rocks that crop out so prominently along the Monterey peninsula make up part of the Salinian block, a crustal terrane that in this area lies west of the San Andreas Fault and east of the San Gregorio Fault. The strike-slip San Andreas Fault Zone, which lies just 26 km east of the map area, is the most important structure within the Pacific–North American transform plate boundary (Dickinson, 2004). The San Gregorio Fault, a secondary fault within the distributed plate boundary, cuts through (and is roughly aligned with) Carmel Canyon, a submarine canyon in the southwest corner of the map area that is part of the Monterey Canyon system. The San Gregorio Fault Zone is part of a fault 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; Johnson and Watt, 2012) to Bolinas and Point Reyes in the north (Bruns and others, 2002; Ryan and others, 2008).

The offshore part of the Offshore of Monterey map area primarily consists of relatively flat continental shelf bounded on the west by the steep flanks of Carmel Canyon. Shelf width varies from 2 to 3 km in the southern part of the map area, near the mouth of Carmel Canyon, to 14 km in Monterey Bay; in those same areas, the shelf dips 2.5° and 0.5°, respectively. Bedrock beneath the shelf is overlain in many areas by variable amounts (0 to 16 m) of upper Quaternary shelf and nearshore sediments deposited as sea level fluctuated in the late Pleistocene. “Soft-induration,” unconsolidated sediment is the dominant (about 63 percent) habitat type on the continental shelf, followed by “hard-induration” rock and boulders (about 34 percent) and “mixed-induration” substrate (about 3 percent) (terminology from Greene and Bizzarro, 2003; see sheet 7 of this report). At water depths of about 100 to 130 m, the shelf break approximates the shoreline during the sea-level lowstand of the Last Glacial Maximum (LGM), about 21,000 years ago (see, for example, Stanford and others, 2011).

Carmel Canyon and other parts of the Monterey Canyon system in the Offshore of Monterey map area extend from the shelf break to water depths that reach 1,600 m. Most of the extensive incision of the shelf break and canyon flanks probably occurred during repeated Quaternary sea-level lowstands. The relatively straight floor of Carmel Canyon notably is aligned with the San Gregorio Fault Zone. Mixed hard-soft substrate is the most common (about 51 percent) habitat type in Carmel Canyon; hard bedrock and soft, unconsolidated sediment cover about 40 percent and 9 percent of canyon habitat, respectively.

This part of the central California coast is exposed to large North Pacific swells from the northwest throughout the year; wave heights range from 2 to 10 m, the larger swells occurring from October to May (Storlazzi and Wingfield, 2005). During El Niño–Southern Oscillation (ENSO) events, winter storms track farther south than they do in normal (non-ENSO) years, thereby impacting the map area more frequently and with waves of larger heights (Storlazzi and Wingfield, 2005).

Benthic species observed in the Offshore of Monterey map area are natives of the cold-temperate biogeographic zone that is called 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, the eastern limb of the North Pacific subtropical gyre that flows from southern British Columbia 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 265 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 of central California has experienced a warming over the last 50 years that is driving an ecosystem shift away from the productive subarctic regime towards a depopulated subtropical environment (McGowan and others, 1998).

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). The kelp beds are well-known habitat for the population of southern sea otters (*Enhydra lutris nereis*) (Tinker and others, 2008). 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).

The offshore part of the map area lies entirely within the Monterey Bay National Marine Sanctuary, one of the nation’s largest marine sanctuaries. State beaches and parks within the map area include Marina State Beach, Fort Ord Dunes State Park, Monterey State Beach, Asilomar State Beach, and Carmel River State Beach, which includes the Carmel River Lagoon and Wetland Natural Preserve. The map area also includes all or part of several State Marine Protected Areas, including the Carmel Pinnacles, Asilomar, and Lovers Point–Julia Platt State Marine Reserves, as well as the Carmel Bay, Pacific Grove Marine Gardens, Edward F. Ricketts, and Portuguese Ledge State Marine Conservation Areas.

Publication Summary

This publication about the Offshore of Monterey 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 deep submarine canyons. To validate the geological and biological interpretations of the sonar data shown in sheets 1, 2, and 3, the U.S. Geological Survey towed a camera sled over specific offshore locations, collecting both video and photographic imagery; these “ground-truth” surveying data are summarized on sheet 6. Sheet 5 is a “seafloor character” map, which classifies the seafloor on the basis of depth, slope, rugosity (ruggedness), and backscatter intensity and which is further informed by the ground-truth-survey imagery. Sheet 7 is a map of marine benthic 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 Pigeon Point to southern Monterey Bay region, interpreted on the basis of the seismic-reflection data. Sheet 10 is a geologic map that merges onshore geologic mapping (compiled from existing maps by the California Geological Survey) and new offshore geologic mapping that is based on integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

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

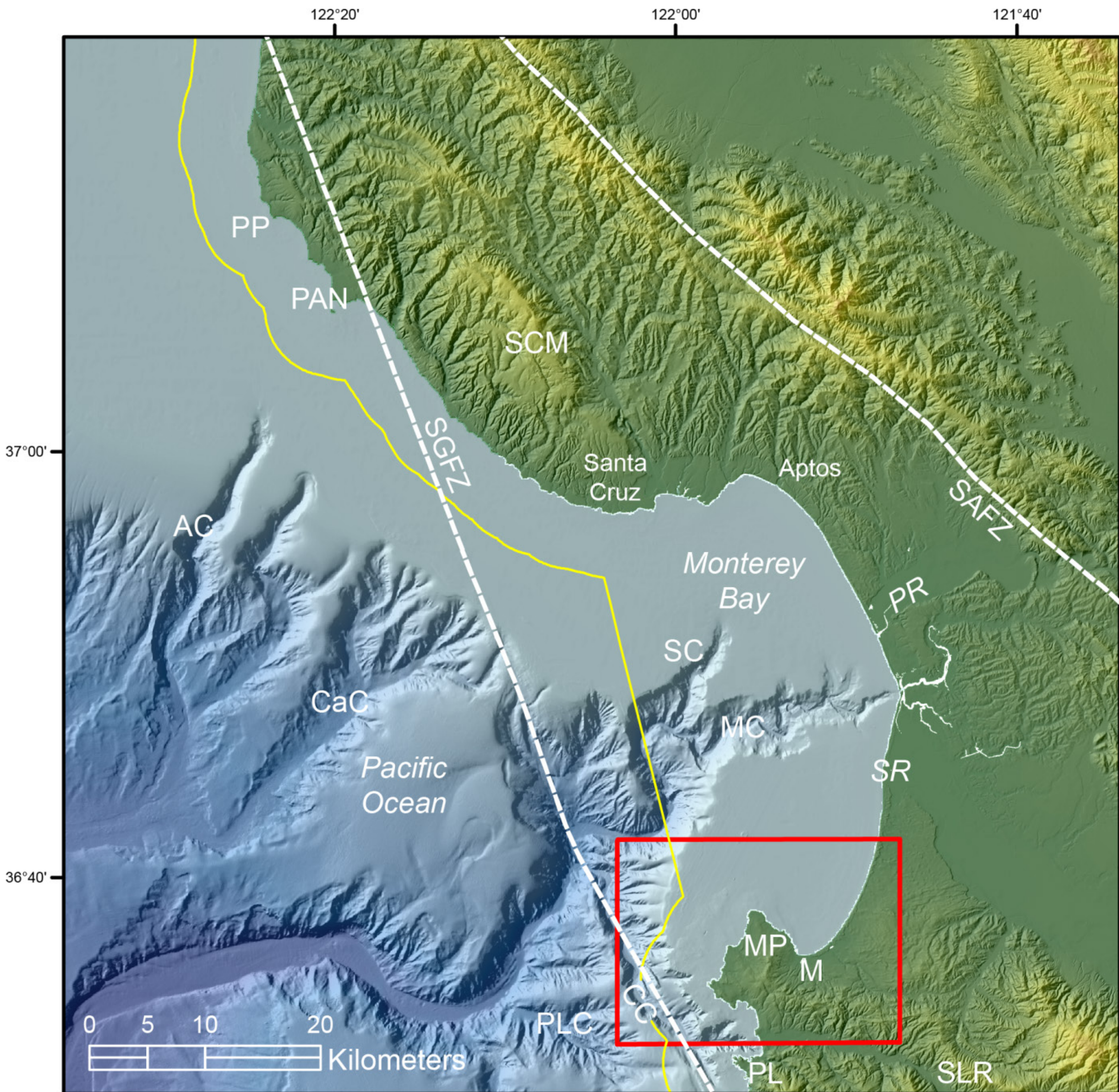


Figure 1–1. Physiography of Pigeon Point to southern Monterey Bay region and its environs. Box shows Offshore of Monterey map area. Yellow line shows limit of California's State Waters. Dashed white lines show traces of San Gregorio Fault Zone (SGFZ) and San Andreas Fault Zone (SAFZ). Other abbreviations: AC, Ascension Canyon; CC, Carmel Canyon; CaC, Cabrillo Canyon; M, Monterey; MC, Monterey Canyon; MP, Monterey peninsula; PAN, Point Año Nuevo; PL, Point Lobos; PLC, Point Lobos canyon; PP, Pigeon Point; PR, Pajaro River; SC, Soquel Canyon; SCM, Santa Cruz Mountains; SLR, Santa Lucia Range; SR, Salinas River.

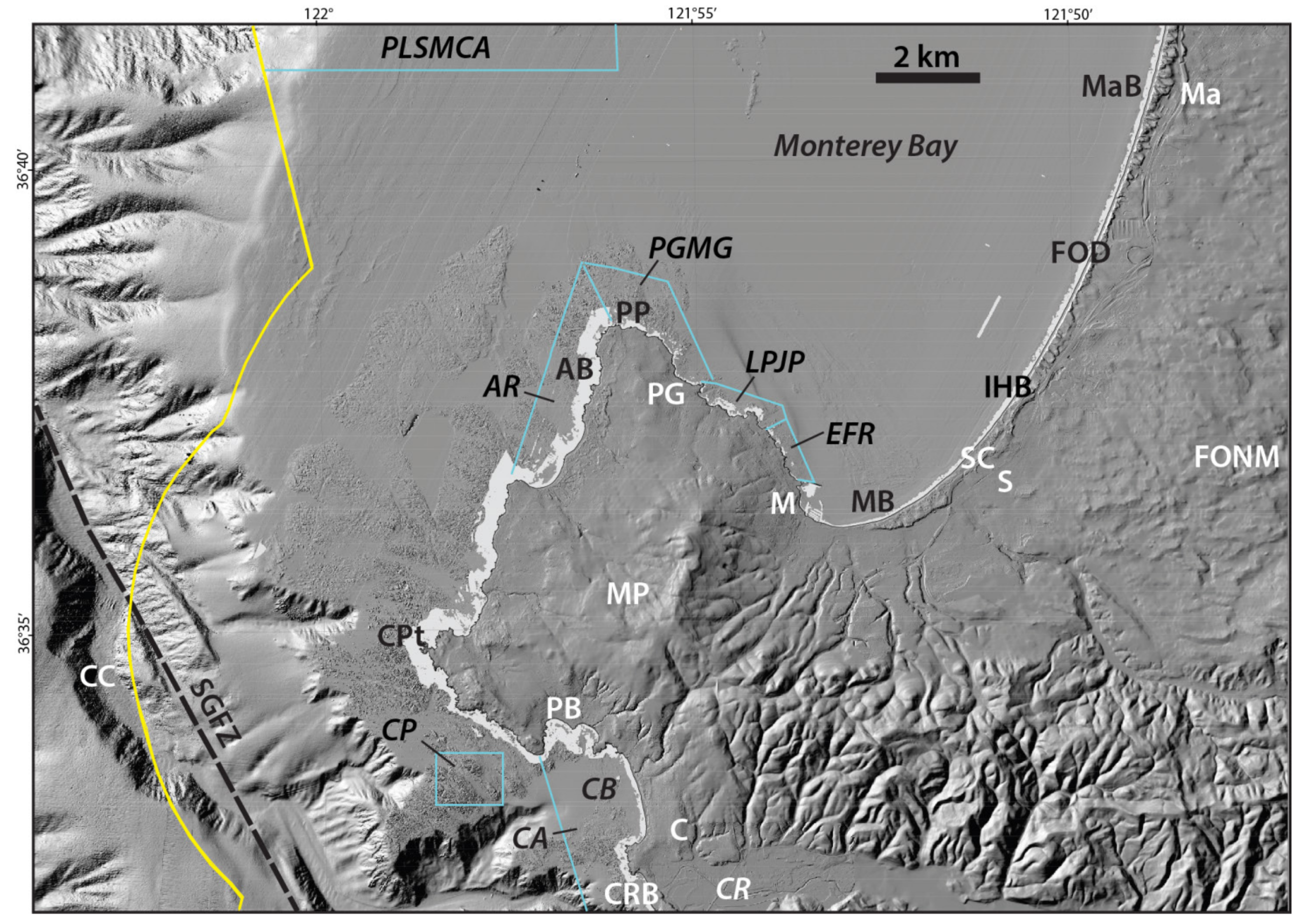


Figure 1–2. Coastal geography of Offshore of Monterey map area. Yellow line shows limit of California's State Waters. Dashed black line shows trace of San Gregorio Fault Zone (SGFZ). Blue lines show boundaries of marine protected areas. Other abbreviations: AB, Asilomar State Beach; AR, Asilomar State Marine Reserve; C, Carmel-by-the-Sea; CA, Carmel Bay State Marine Conservation Area; CB, Carmel Bay; CC, Carmel Canyon; CP, Carmel Pinnacles State Marine Reserve; CPt, Cypress Point; CR, Carmel River; CRB, Carmel River State Beach; EFR, Edward F. Ricketts State Marine Conservation Area; FOD, Fort Ord Dunes State Park; FONM, Fort Ord National Monument; IHB, Indian Head Beach; LPJP, Lovers Point–Julia Platt State Marine Reserve; M, Monterey; Ma, Marina; MaB, Marina State Beach; MB, Monterey State Beach; MP, Monterey peninsula; PB, Pebble Beach; PG, Pacific Grove; PGMG, Pacific Grove Marine Gardens State Marine Conservation Area; PLSMCA, Portuguese Ledge State Marine Conservation Area; PP, Point Pinos; S, Seaside; SC, Sand City.

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

By Peter Dartnell and Rikk G. Kvitek

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of Monterey map area in central California were generated from both acoustic-bathymetry and acoustic-backscatter data collected by California State University, Monterey Bay (CSUMB), and by Monterey Bay Aquarium Research Institute (MBARI) (fig. 1 on sheets 1, 2, 3). Bathymetric-lidar data was also collected in the nearshore area by the U.S. Army Corps of Engineers Joint Airborne Lidar Bathymetry Technical Center of Expertise. Acoustic mapping was completed between 1998 and 2012, using a combination of 200-kHz/400-kHz Reson 7125, 240-kHz Reson 8101, and 30-kHz Simrad EM-300 multibeam echosounders, as well as 234-kHz and 468-kHz SEA SWATHplus bathymetric sidescan-sonar systems. Bathymetric-lidar mapping was completed in 2009 and 2010 for the California Coastal Mapping Project. These mapping missions combined to collect bathymetry data from the shoreline (sheets 1, 2), as well as acoustic-backscatter data from about the 10-m isobath (sheet 3), to beyond the limit of California's State Waters (note that the California's State Waters limit, which generally is 3 nautical miles [5.6 km] from shore, extends farther offshore (as much as 12 nautical miles) between Santa Cruz and Monterey, so that it encompasses all of Monterey Bay; see figs. 1–1, 1–2).

During the CSUMB mapping missions between 2000 and 2012, either an Applanix POS MV (Position and Orientation System for Marine Vessels) or a Teledyne TSS HDMS (Hydrographic Data Maintenance System) was used to accurately position the vessels during data collection, and they also accounted for vessel motion such as heave, pitch, and roll, with navigational input from Trimble 4700 GPS or CNAV®-enabled NavCon 2050 GPS receivers. Kinetic GPS (KGPS) altitude data were used to account for tide-cycle fluctuations, and sound-velocity profiles were collected with an Applied Microsystems (AM) SVPlus sound velocimeter. Soundings were corrected for vessel motion using the Applanix POS MV or Teledyne TSS HDMS 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 postprocessed GPS data (California State University, Monterey Bay, Seafloor Mapping Lab, 2015).

The Reson backscatter data were postprocessed using a variety of methods, which include Geocoder, Isis Sonar, Delph Map, and TNT Mips geographic information system (GIS) software. For the data postprocessed using Geocoder, the backscatter intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. After the lines were corrected, they were mosaicked into 1- or 2-m-resolution images. Overlap between parallel lines was resolved using a priority table whose values were based on the distance of each sample from the ship track, with the samples that were closest to and furthest from the ship track being given the lowest priority. An anti-aliasing algorithm was also applied. The mosaics were then exported as georeferenced TIFF images, imported into a GIS, and converted to GRIDs at 2-m resolution (California State University, Monterey Bay, Seafloor Mapping Lab, 2015).

For the backscatter data postprocessed using the Isis Sonar, Delph Map, and TNT Mips methods, individual tracklines were replayed, and the bottom tracking of the sonar was supervised to aid in proper slant-range correction. Line files were snipped to remove parts that have poor imagery from the beginning and (or) end of the tracklines. Tracklines then were corrected for slant range and layback, and the position data for each line was smoothed using a speed filter. Each line was then gridded, georeferenced, and exported from Isis Sonar or Delph Map in GeoTIFF format. Individual trackline

TIFF images were imported into TNT Mips GIS software, and areas of poor image quality were extracted and removed. Individual tracklines were then overlaid to produce a mosaic image. GeoTIFFs were exported from TNT Mips, imported into a GIS, and converted to GRIDs at 2-m spatial resolution (California State University, Monterey Bay, Seafloor Mapping Lab, 2015).

The SWATHPlus backscatter data were postprocessed using USGS software (D.P. Finlayson, written commun., 2011) that normalizes for time-varying signal loss and beam directivity differences. Thus, the raw 16-bit backscatter data were gain-normalized to enhance the backscatter of the SWATHplus system. The resulting normalized-amplitude values were rescaled to 16-bit and gridded into GeoJPEGs using GRID Processor Software, then imported into a GIS and converted to GRIDS (California State University, Monterey Bay, Seafloor Mapping Lab, 2015).

During the MBARI mapping mission in 1998, an Applied Analytic POS MV was used to accurately position the vessel during data collection, and it also accounted for vessel motion with navigational input from a kinematic differential GPS (DGPS) system. Soundings were corrected for variations in water-column sound velocity using data from SeaBird CTD and Sippican T5 expendable bathythermographs. The USGS downloaded the original MBARI survey line files from the National Centers for Environmental Information’s online bathymetry server (National Centers for Environmental Information, 2015). Using MB-Systems, bathymetry and amplitude values were extracted from the line files and exported as bathymetry and amplitude XYZ files.

Nearshore bathymetric-lidar data and acoustic-bathymetric data from within California’s State Waters were merged together as part of the 2013 National Oceanic and Atmospheric Administration (NOAA) Coastal California TopoBathy Merge Project (National Oceanic and Atmospheric Administration, 2013). Merged bathymetry data from within the Offshore of Monterey map area were downloaded from this dataset and resampled to 2-m spatial resolution, then the deeper MBARI, 5-m-resolution bathymetric data outside of California’s State Waters. An illumination having an azimuth of 300° and from 45° above the horizon was then applied to the bathymetric surfaces to create the shaded-relief imagery (sheets 1, 2). In addition, a “rainbow” color ramp was applied to the bathymetry data for sheet 1, using reds to represent shallower depths, and purples to represent greater depths. This colored bathymetry surface was draped over the shaded-relief imagery at 60-percent transparency to create a colored shaded-relief map (sheet 1). Note that the ripple patterns and parallel lines that are apparent within the map area are data-collection and -processing artifacts. These various artifacts are made obvious by the hillshading process.

Bathymetric contours (sheets 1, 2, 3, 5, 7, 10) were generated from the modified 2- and 5-m-resolution bathymetric surfaces. Contours were generated at 10-m intervals for water depths shallower than 100 m, at 50-m intervals for water depths between 100 and 200 m, and at 200-m intervals in water depths deeper than 200 m. 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 contours were then clipped to the boundary of the map area.

The acoustic-backscatter imagery from each different mapping system and processing method were merged into their own individual grids. These individual grids, which cover different areas, were displayed in a GIS to create a composite acoustic-backscatter map (sheet 3). On the map, 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 composition. 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). Ripple patterns and straight lines in some parts of the map area are data-collection and -processing artifacts.

The onshore-area image was generated by applying an illumination having an azimuth of 300° and from 45° above the horizon to 2-m-resolution topographic-lidar data from National Oceanic and Atmospheric Administration Office for Coastal Management's Digital Coast (available at http://www.csc.noaa.gov/digitalcoast/data/coastallidar/) and to 10-m-resolution topographic-lidar data from the U.S. Geological Survey's National Elevation Dataset (available at http://ned.usgs.gov/).

Chapter 3. Data Integration and Visualization for the Offshore of Monterey 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 Monterey 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 Monterey 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). In some views (figs. 2, 3, 4), the bathymetry was color-coded to closely match the colored shaded-relief bathymetry on sheet 1, in which reds represent shallower depths and purples represent deeper depths. Acoustic-backscatter geoTIFF images also were draped over the bathymetry data (fig. 4). Onshore topographic data were shown in gray shades. The bathymetry, topography, and draped backscatter were then tilted and panned to create the perspective views such as those shown in figures 1 through 5 on sheet 4. These view highlight the seafloor morphology in the Offshore of Monterey map area, which includes complex patterns of scour depressions, extensive areas of rocky outcrop, and the head of Carmel Canyon.

Video-mosaic images created from digital seafloor video can display the geologic 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 above the seafloor, at speeds less than 1 nautical mile/hour. High-resolution digital terrain models (DTMs; fig. 6) were generated from the seafloor video using Structure from Motion (SfM) techniques from Agisoft PhotoScan software (v. 1.2.4). SfM techniques generate three-dimensional models from overlapping two-dimensional images. The seafloor video was converted to AVI format using FF-MPEG software, then it was converted to individual frames using software developed by Yuri Rzhanov at the Center for Coastal and Ocean Mapping, University of New Hampshire, through a joint U.S. Geological Survey–University of New Hampshire cooperative agreement. Every fifth frame was loaded into the SfM software; frame spacing was determined by the overlap between frames, ensuring that specific seafloor features were observed within 4 to 5 frames. A three-dimensional bathymetric model was created from the video frames using the following five stages: alignment of the camera, generation of a sparse point cloud, generation of a dense point cloud, building of a mesh, and, finally, export of the dense point cloud as an XYZ ASCII file, in relative coordinates. The XYZ file was converted to a bathymetric surface using Fledermaus® software (QPS) then exported as an ASCIIRASTER file and imported into a GIS (ESRI's ArcMap, v. 10.1) and converted to a GRID in relative coordinates. The GRID was rectified using the georeferencing tool in ArcMap and navigational coordinates that were recorded at the time of the video survey. The final, georeferenced bathymetric surface has a spatial resolution of 20 cm.

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

By Mercedes D. Erdey and Guy R. Cochrane

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

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

The following four substrate classes are identified in the Offshore of Monterey 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 Monterey 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. The rugosity calculation was performed using the Terrain Ruggedness (VRM) tool within the Benthic Terrain Modeler toolset v. 3.0 (Wright and others, 2012; available at http://esriurl.com/5754).

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 Monterey map area, Depth Zones 2 through 5 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 Monterey map area, Slope Classes 1 through 3 are present. The final classified seafloor-character raster map image has been draped over the shaded-relief bathymetry for the area (sheets 1 and 2) to produce the image shown on the seafloor-character map on sheet 5.

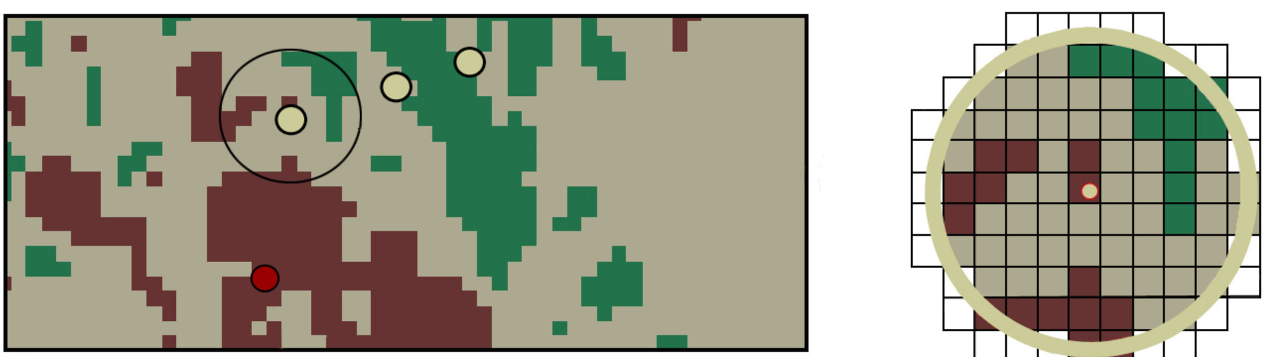
The seafloor-character classification also is summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 62.1 percent (160.8 km^2) of the map area: 9.5 percent (24.6 km^2) is in Depth Zone 2, 25.2 percent (65.4 km^2) is in Depth Zone 3, 7.3 percent (19.0 km^2) is in Depth Zone 4, and 20.0 percent (51.9 km^2) is in Depth Zone 5. 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 17.2 percent (44.6 km^2) of the map area: 1.4 percent (3.6 km^2) is in Depth Zone 2, 4.7 percent (12.2 km^2) is in Depth Zone 3, 3.3 percent (8.6 km^2) is in Depth Zone 4, and 7.8 percent (20.2 km^2) is in Depth Zone 5. Rock and boulder, rugose (rock and boulder outcrops having high surficial complexity) makes up 15.9 percent (41.2 km^2) of the map area: 2.9 percent (7.5 km^2) is in Depth Zone 2, 5.1 percent (13.3 km^2) is in Depth Zone 3, 0.4 percent (1.0 km^2) is in Depth Zone 4, and 7.5 percent (19.3 km^2) is in Depth Zone 5. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than the surrounding seafloor) makes up 4.8 percent (12.5 km^2) of the map area: 0.5 percent (1.2 km^2) is in Depth Zone 2, 4.3 percent (11.0 km^2) is in Depth Zone 3, and 0.1 percent (0.3 km^2) is in Depth Zone 4.

A small number of video observations and sediment samples 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 Monterey map area is a combination of the sediment-dominated (Class I) parts of the Offshore of Monterey map area and the rocky (Class III) underwater extension of the Monterey peninsula. Most of the deeper areas in Monterey Bay (in the northeastern part of the map area) are mainly flat, predominantly covered by Class I sediment composed of soft, unconsolidated sand and interspersed with local, small sedimentary-bedrock exposures (Class II and III). The west half of the offshore map area consists of patchy bedrock (Class II and III). Exposed rock is covered intermittently by varying thicknesses of fine- (Class I) to coarse-grained (Class II) sediment (coarse sand, gravel, and cobbles). Several scour depressions (mobile sedimentary features, Class IV) are dispersed in the shallow nearshore area (intertidal to 30 m), predominantly along the parts of the Monterey Bay and Monterey peninsula coastlines that face northwest.

The classification of Class I sediments was found to be moderately accurate (2-m-resolution grid, 69 percent accurate; 5-m-resolution grid, 84 percent accurate; table 4–2), as determined by comparing the shipboard video observations and the classified map. The classification of Class II sediments was weaker (2-m-resolution grid, 59 percent accurate; 5-m-resolution grid, 6 percent accurate); the poor agreement for the 5-m-resolution grid likely is due to the presence of gravels as a secondary substrate in the video observations in a 5-m-resolution grid area that was classified as Class I. The classification of Class III rugose rock and boulders was found to be moderately accurate (2-m-resolution grid, 65 percent accurate; 5-m-resolution grid, 60 percent accurate). Most of the bedrock in the map area is granitic rock, which tends to have a smooth surface. Fractures in the granitic rock create rugosity, but they also can be filled with Class I and II sediments, resulting in patchy areas of rugosity on the seafloor. A single buffered observation locale of 78 pixels, therefore, is likely to be interspersed with other classes of pixels, in addition to Class III. The classification of Class IV sediments was found to be moderately accurate (2-m-resolution grid, 90 percent accurate; 5-m-resolution grid, 57 percent accurate). Class IV areas were identified in the video observations by the presence of large bedforms and bedform-related



A *B*

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. Green color represents Class I sediments; tan color represents Class II sediments; and red color represents Class III sediments.

changes in sediment grain size, as well as by the presence of shell hash; however, some parts of scour depressions consist of homogeneous sand. Homogeneous deposits of sand are identified as Class I in video observations, thereby reducing the accuracy assessment for Class IV.

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 that have video observations within the coverage of the 2-m-resolution seafloor-character map (84 percent for Class I, 80 percent for Class II, 92 percent for Class III, and 90 percent for Class IV). Within the coverage of the 5-m-resolution seafloor-character map, the presence/absence accuracy also was found to be significant for Classes I and II (84 percent for Class I, and 83 percent for Class III). The accuracy percentage for Class II increased to 22 percent. Class IV accuracy was 57 percent for presence/absence, the same value as the majority accuracy value for that class in the 5-m-resolution grid. Class IV accuracy numbers are not improved by a presence/absence test because areas of homogeneous sand are not patchy.

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 Monterey 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	
mud	sand	low	
sand	mud	low	
sand	sand	low	
sand	sand	moderate	
			sand
Class II			
cobbles	sand	moderate	
cobbles	gravel	low	
cobbles	gravel	moderate	
gravel	boulders	low	
gravel	cobbles	low	
gravel	rock	low	
gravel	sand	low	
mud	cobbles	low	
rock	gravel	low	
rock	sand	low	
rock	rock	low	
sand	cobbles	low	
sand	gravel	low	
sand	gravel	moderate	
sand	rock	low	

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 Monterey map area.—Continued

Primary-substrate component	Secondary-substrate component	Abiotic seafloor complexity	Low-visibility observations
Class III			
boulders	boulders	high	
boulders	boulders	moderate	
boulders	cobbles	high	
boulders	cobbles	moderate	
boulders	gravel	moderate	
boulders	rock	moderate	
boulders	sand	moderate	
cobbles	boulders	moderate	
cobbles	rock	moderate	
rock	boulders	high	
rock	boulders	moderate	
rock	cobbles	high	
rock	cobbles	moderate	
rock	gravel	moderate	
rock	rock	high	
rock	rock	moderate	
rock	sand	high	
rock	sand	moderate	
sand	boulders	moderate	
sand	rock	high	
sand	rock	moderate	

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

[Accuracy assessments are based on video observations]

Class	Number of observations	% majority	% presence/absence
2-m-resolution grid			
I—Fine- to medium-grained smooth sediment	172	69.2	83.1
II—Mixed smooth sediment and rock	78	59.0	79.5
III—Rock and boulder, rugose	133	64.7	92.5
IV—Medium- to coarse-grained sediment (in scour depressions)	20	90.0	90.0
5-m-resolution grid			
I—Fine- to medium-grained smooth sediment	121	83.5	84.3
II—Mixed smooth sediment and rock	46	6.5	21.7
III—Rock and boulder, rugose	30	60.0	83.3
IV—Medium- to coarse-grained sediment (in scour depressions)	7	57.1	57.1

Chapter 5. Ground-Truth Studies for the Offshore of Monterey 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 Monterey map area to collect video and photographic data that would "ground truth" the seafloor. This ground-truth surveying occurred in 2010 and 2012. The camera sled was towed 1 to 2 m above the seafloor, at speeds of between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 24 trackline kilometers of video and 7,400 still photographs, in addition to 818 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

During the ground-truth survey cruises, the USGS camera sled 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 these cruises, in addition to recording the seafloor characteristics, a digital still photograph was captured once every 30 seconds.

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

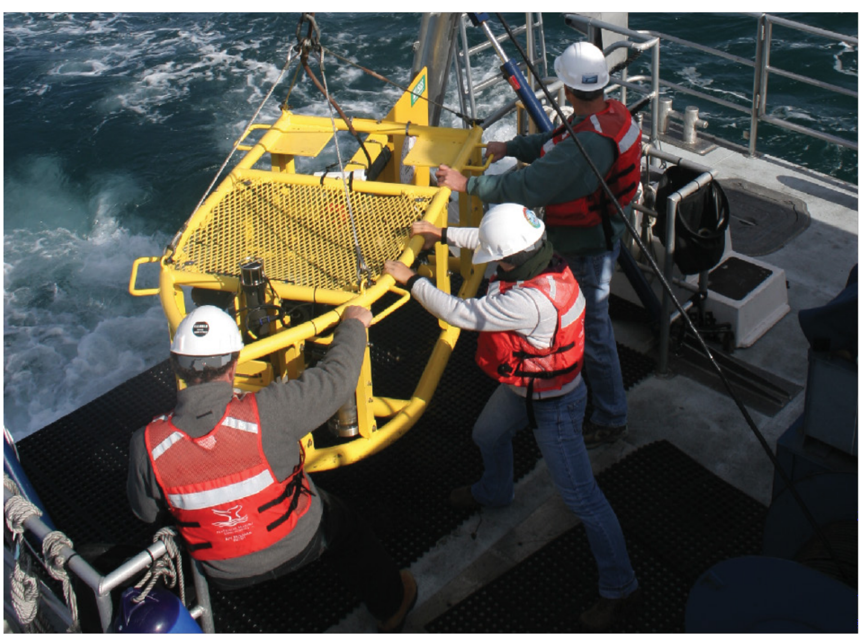


Figure 5–1. Photograph of camera sled being prepared to be launched off ship for ground-truth survey.

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 seafloor in the Offshore of Monterey map area is dominated by mud and sand, with lesser amounts of rock and minor gravel, boulders, and cobbles (see also, sheets 5, 7, 10).

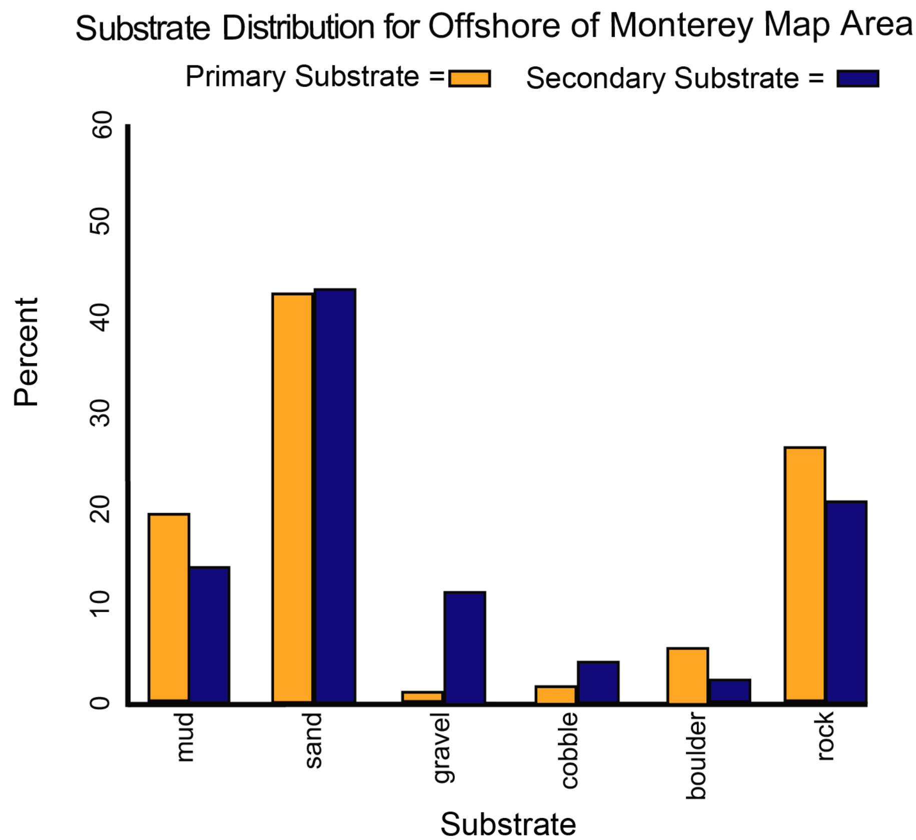


Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Monterey map area.

Chapter 6. Marine Benthic Habitats of the Offshore of Monterey Map Area (Sheet 7)

By Guy R. Cochrane and Stephen R. Hartwell

The map on sheet 7 shows physical marine benthic habitats in the Offshore of Monterey map area. Marine benthic habitats represent a particular type of, substrate and geomorphology attribute that may provide a habitat for a specific species or assemblage of organisms. Marine benthic habitats are classified using the Coastal and Marine Ecological Classification Standard (CMECS), developed by representatives from a consortium of Federal agencies. CMECS is the Federal standard for marine habitat characterization (available at https://www.fgdc.gov/standards/projects/FGDC-standards-projects/cmecs-folder/CMECS_Version_06-2012_FINAL.pdf). The standard provides an ecologically relevant structure for biologic-, geologic-, chemical-, and physical-habitat attributes.

The map illustrates the geoform and substrate components of the standard and their distribution in the Offshore of Monterey map area. Geoform components describe the major geomorphic and structural characteristics of the coast and seafloor (that is, the tectonic and physiographic settings and the geological, biogenic, and anthropogenic features). The map was derived from the geologic and geomorphic map of the seafloor (see sheet 10) by translation of the map-unit descriptions into the best-fit values of the CMECS classes. The map also includes a temporal attribute for each unit that indicates time period of persistence, as well as an induration attribute that allows resymbolization of the data-catalog shapefile into a simple map of hard-mixed-soft attributes essential for fish-habitat assessment.

CMECS codes are provided in the data-catalog shapefile and in table 6–1 (the CMECS coding system is described at https://coast.noaa.gov/digitalcoast/sites/default/files/files/publications/21072015/CMECS_Coding_System_Approach_20140619.pdf). Note that the CMECS codes are designed to facilitate database searching and sorting but are not used for map symbolization on the benthic habitat map (sheet 7); instead, polygons are labeled with a letter that identifies the CMECS physiographic setting (B, bay; S, continental shelf; C, canyon) and a sequential number for each map unit within that setting (table 6–1).

Map Area Habitats

The Offshore of Monterey map area includes the nearshore and inner continental shelf areas in southern Monterey Bay and surrounding the Monterey peninsula, as well as Carmel Canyon, a tributary of Monterey Canyon. Delineated on the map are 16 marine benthic habitat types: 8 types are located on the continental shelf, 6 are located within submarine canyons, and 2 are located in Monterey Bay (table 6–1; see also, table 1 on sheet 7). The habitats include soft, unconsolidated sediment (9 habitat types) such as fine sand and mud and also just sand, as well as dynamic features such as mobile sand sheets, sediment waves, and rippled sediment depressions; mixed substrate (3 habitat types) such as sand and gravels that overlie hard consolidated sedimentary bedrock; and hard substrate (3 habitat types) such as bedrock and boulders. Three anthropogenic features (wharves) are present in the map area.

Of the total of 269 km^2 mapped in the Offshore of Monterey map area, 165.5 km^2 (61.6 percent) is mapped in the continental shelf setting, 4.8 km^2 (1.8 percent) is mapped in the bay setting, and 98.3 km^2 (36.6 percent) is mapped in the canyon setting. In the continental shelf and bay settings, “soft-induration,” unconsolidated sediment is the dominant habitat type, covering 106.9 km^2 (62.8 percent); “mixed-induration” substrate covers 5.3 km^2 (3.1 percent); and “hard-induration” rock and boulders covers 53.2 km^2 (34.1 percent) (terminology from Greene and Bizzarro, 2003). In Carmel Canyon, mixed hard-soft substrate is the dominant habitat type, covering 49.7 km^2 (50.6 percent); unconsolidated sediment and hard rock cover a total of 9.0 km^2 (9.1 percent) and 39.6 km^2 (40.3 percent), respectively.

Note that a higher amount of “hard-induration” substrate is found in this map area than is typically found in California’s State Waters. Anthropogenic substrate covers 0.05 km^2 and, thus, is not significant.

Table 6–1. Marine benthic habitats from Coastal and Marine Ecological Classification Standard mapped in Offshore of Monterey map area, showing description and total area, in square meters, of each.

Map-unit label	CMECS code	Description	Area, in square meters
B1	Gt8p9g1.50S1.1.1SI1P10	Transform Continental Margin. Embayment/Bay. Rock Outcrop. Bedrock. Hard Substrate Induration. Centuries Persistence	4,785,832
B2	Gt8p9g3.15P9	Transform Continental Margin. Embayment/Bay. Wharf. Decades Persistence	49,947
S1	Gt8p6g1.49S1.2.2.2.3SI3P9	Transform Continental Margin. Continental/Island Shelf. Ripples. Medium Sand. Soft Substrate Induration. Decades Persistence	79,625,410
S2	Gt8p6g1.49g1.64S1.2.2.2.3S1.1.1SI2P8	Transform Continental Margin. Continental/Island Shelf. Ripples. Rock Outcrop. Medium Sand. Bedrock. Mixed Substrate Induration. Years Persistence	5,326,584
S3	Gt8p6g1.50S1.1.1SI1P10	Transform Continental Margin. Continental/Island Shelf. Rock Outcrop. Bedrock. Hard Substrate Induration. Centuries Persistence	53,214,811
S4	Gt8p6g1S1.2.1.2.1SI2p9	Transform Continental Margin. Continental/Island Shelf. Sandy Gravel. Soft Substrate Induration. Decades Persistence	942,202
S5	Gt8p6g1S1.2.2.4.2SI3P9	Transform Continental Margin. Continental/Island Shelf. Sandy Silt-Clay. Soft Substrate Induration. Decades Persistence	18,252,877
S6	Gt8p6g1.14.1S1.2.1.3.1SI3P9	Transform Continental Margin. Continental/Island Shelf. Scour Depression. Gravelly Sand. Soft Substrate Induration. Decades Persistence	8,081,663
S7	Gt8p6g1.61S1.2.1.3.2SI3P10	Transform Continental Margin. Continental/Island Shelf. Slope. Gravelly Muddy Sand. Soft Substrate Induration. Centuries Persistence	5,133
S8	Gt8p6g1.66.2S1.2.1.3.2SI3P10	Transform Continental Margin. Continental /Island Shelf. Wave Built Terrace. Gravelly Muddy Sand. Soft Substrate Induration. Centuries Persistence	13,423
C1	Gt8p20g1.34S1.2.2.3SI3P1	Transform Continental Margin. Submarine Canyon. Ledge. Muddy Sand. Soft Substrate Induration. Stochastic Persistence	18,678
C2	Gt8p20g1.45S1.2.2.4.2SI3P1	Transform Continental Margin. Submarine Canyon. Platform. Sandy Silt-Clay. Soft Substrate Induration. Stochastic Persistence	8,389,367
C3	Gt8p20g1.50S1.1.1SI1P9	Transform Continental Margin. Submarine Canyon. Rock Outcrop. Bedrock. Hard Substrate Induration. Decades Persistence	38,612,048
C4	Gt8p20g1.37S1.2.2.2SI3P1	Transform Continental Margin. Submarine Canyon. Megaripples. Sand. Soft Substrate Induration. Stochastic Persistence	569,767
C5	Gt8p20g1.37g1.64S1.2.2.1.1S1.1.1SI2P1	Transform Continental Margin. Submarine Canyon. Megaripples. Submarine Slide Deposit. Slightly Gravelly Sand. Bedrock. Mixed Substrate Induration. Stochastic Persistence	5,082,653
C6	Gt8p20g1.64S1.2.2.4.2S1.1.1SI2P1	Transform Continental Margin. Submarine Canyon. Submarine Slide Deposit. Sandy Silt-Clay. Bedrock. Mixed Substrate Induration. Stochastic Persistence	45,648,184

Chapter 7. Subsurface Geology and Structure of the Offshore of Monterey Map Area and the Pigeon Point to Southern Monterey Bay Region (Sheets 8 and 9)

By Samuel Y. Johnson, Janet T. Watt, Stephen R. Hartwell, and Katherine L. Maier

The seismic-reflection profiles presented on sheet 8 provide a third dimension—depth beneath the seafloor—to complement the surficial seafloor-mapping data already presented (sheets 1 through 7) for the Offshore of Monterey 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 (see, for example, Petersen and others, 2014).

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

Data Acquisition

Most profiles displayed on sheet 8 (figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13) were collected in 2011 on U.S. Geological Survey (USGS) cruise S–6–11–MB (Sliter and others, 2013), using the SIG 2Mille minisparker system. This system used a 500-J high-voltage electrical discharge fired 1 to 2 times per second, which, at normal survey speeds of 4 to 4.5 nautical miles per hour, gives a data trace every 1 to 2 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). These data can resolve geologic features a few meters thick (and, hence, are considered “high-resolution”), down to subbottom depths of as much as 400 m.

Figure 11 on sheet 8 shows a migrated, deep-penetration, multichannel seismic-reflection profile collected in 1982 by WesternGeco on cruise W–34–82–MB. 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 (Triezenberg and others, 2016). 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 as much as 4 km.

Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Monterey map area, providing an image of the subsurface geology. The continental shelf in the map area is incised by the Monterey Canyon system and its tributaries, including Carmel Canyon. Outside of this canyon system, the shelf extends from the shoreline to water depths of about 100 to 120 m. Shelf slope ranges from as little as 0.5° offshore of Marina to as much as 3.8° offshore of the west flank of the Monterey peninsula. The shelf is underlain by Cretaceous granitic basement rocks, Tertiary sedimentary rocks, and uppermost Pleistocene to Holocene sediments (see sheet 10). Granitic basement rocks are characterized as massive, reflection-free zones (see, for example, figs. 3, 5, 6, 11 on sheet 8). Tertiary sedimentary rocks, which predominantly consist of the Miocene Monterey Formation and the Miocene and Pliocene Purisima Formation, are characterized on high-resolution and multichannel seismic-reflection profiles (see, for example, figs. 1, 2, 3, 5, 7, 8, 10, 13 on sheet 8) by parallel to subparallel, continuous, variable-amplitude, high-frequency reflections (terminology from Mitchum and others, 1977). The seismic-reflection data reveal that these rocks are typically flat lying to gently folded and are cut by high-angle faults.

Eustasy was an important control on latest Pleistocene to Holocene shelf deposition in the Offshore of Monterey map area. Surficial and shallow sediments were deposited on the shelf in the last about 21,000 years during the sea-level rise that followed the last major lowstand and the Last Glacial Maximum (LGM) (Stanford and others, 2011). Global sea level was about 120 to 130 m lower during the LGM, at which time the shelf surrounding Monterey Canyon system was emergent. 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 (Peltier and Fairbanks, 2006; Stanford and others, 2011). The sediments deposited on the shelf during the post-LGM sea-level rise (above a transgressive surface of erosion) are shaded blue in many of the high-resolution seismic-reflection profiles (figs. 1, 2, 3, 5, 7, 8, 9, 12, 13 on sheet 8), and their thicknesses are shown on sheet 9.

Post-LGM shelf sediments unconformably overlie both bedrock and Pleistocene paleochannel deposits in the Offshore of Monterey map area. Throughout the map area, the contact between bedrock and the overlying upper Quaternary sediments (where present) is an angular unconformity that commonly is marked by minor channeling and an upward change to lower amplitude, more diffuse reflections. Over much of the map area, these sediments form a thin layer over bedrock that was beveled during the post-LGM transgression (sheet 9). Mean thickness of the post-LGM sediment in the map area is 2.2 m (table 7–1); thickest sediment (about 16 m) is found in an oval depression on the flank of granitic rocks 2 km north of the northernmost tip of the Monterey peninsula (see fig. 5 on sheet 8; see also, fig. 1 and Map B on sheet 9).

Seismic-Reflection Imaging of Carmel Canyon

Monterey Canyon and its tributaries, including Carmel Canyon, incise bedrock and sediments through the continental shelf in the Offshore of Monterey map area, creating as much as several hundreds of meters of relief on the seafloor. Although several high-resolution seismic-reflection profiles cross parts of Carmel Canyon, their quality and resolution is less than that of adjacent seismic-reflection data on the shelf. In addition, reflection-free granitic rocks form much of the east wall of Carmel Canyon, and their steep relief creates widespread side-echoes and diffractions that significantly diminish data quality. One deep-penetration, multichannel seismic-reflection profile crosses Carmel Canyon (fig. 11 on sheet 8); this profile images reflections at a larger scale and a lower resolution than that of the high-resolution seismic-reflection profiles.

Geologic Structure and Recent Deformation

The shelf northeast and north of the Monterey peninsula is cut by the diffuse zone of northwest-striking, steeply dipping to vertical faults of the Monterey Bay Fault Zone. The fault strands are identified in seismic-reflection profiles on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as amplitude, frequency, geometry, continuity, and vertical sequence. The Monterey Bay Fault Zone, originally mapped by Greene (1977, 1990), extends about 45 km across outer Monterey Bay (see Map E on sheet 9). To the south-southeast, the fault connects with the Navy, Chupines, Seaside, and Ord Terrace Faults onland (see sheet 10). Seismic-reflection profiles in the map area that traverse this diffuse zone cross as many as five faults over a width of about 4 to 5 km (see, for example, figs. 3, 5 on sheet 8). The Monterey Bay Fault Zone lacks a continuous "master fault" along which deformation is concentrated; fault strands are as long as about 20 km (on the basis of mapping outside the map area), but most strands are only about 2 to 7 km long. Faults in this diffuse zone cut through Neogene bedrock, and they locally appear to have minimally disrupted the overlying inferred Quaternary sediments. The presence of warped reflections along some fault strands suggests that both vertical and strike-slip offset may have occurred.

West of the Monterey peninsula, the northwest-striking San Gregorio Fault Zone extends roughly parallel to the axis of Carmel Canyon. The San Gregorio Fault Zone is an important structure in the distributed transform boundary between the North American and Pacific plates (see, for example, Dickinson and others, 2005). It is part of the San Gregorio–Hosgri Fault system, which is present predominantly in the offshore for about 400 km, from Point Conception in the south (where it is known as the Hosgri Fault; Johnson and Watt, 2012) to Bolinas and Point Reyes in the north (Bruns and others, 2002; Ryan and others, 2008). The San Gregorio Fault Zone in the map area is part of a 90-km-long offshore segment that extends northward from Point Sur (about 25 km south of the map area), across outer Monterey Bay to Point Año Nuevo (about 50 km north of the map area) (see sheet 9; see also, Weber and Lajoie, 1980; Brabb and others, 1998; Wagner and others, 2002). The San Gregorio Fault Zone is not well imaged in the map area, on either high-resolution (see, for example, fig. 12 on sheet 8) or deep-penetration (fig. 11 on sheet 8) seismic-reflection profiles because of its location in steep-sided Carmel Canyon and also because it cuts through reflection-free granitic basement rocks along the east wall of the canyon. Accordingly, we have mapped the 1,000- to 1,300-m-wide fault zone largely on the basis of the presence of prominent, lengthy geomorphic lineaments (see sheets 1, 2), as well as the geomorphic and lithologic contrasts across the fault (see sheet 10).

Map E on sheet 9 shows the regional pattern of major faults and recorded earthquakes. Fault locations, which have been simplified, are compiled from our mapping within California's State Waters (see sheet 10), from Wagner and others (2002), 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 that have inferred or measured magnitudes of 2.0 and greater for the time period 1967 through April 2014 are shown. The 1989 Loma Prieta earthquake (M6.9, 10/17/1989), on the San Andreas Fault Zone in the Santa Cruz Mountains (Spudich, 1996), is the most significant event in the region. The largest recorded earthquake in the Offshore of Monterey map area (M3.4, 12/30/1974) occurred onshore in the Monterey Bay Fault Zone, near the city of Monterey.

Thickness and Depth to Base of Uppermost Pleistocene and Holocene Deposits

Maps on sheet 9 show the interpreted thickness and the depth to base of uppermost Pleistocene and Holocene deposits, both for the Offshore of Monterey map area (Maps A, B) and, to establish regional context, for a larger area that extends about 91 km along the coast from the Pigeon Point area to southern Monterey Bay (Maps C, D). Note that mapping, which is based on high-resolution seismic-reflection profiles (sheet 8), is restricted to the continental shelf; data from within the Monterey Canyon system (including Carmel Canyon), in the southern part of the Pigeon Point to southern Monterey Bay region, were excluded from this analysis because available seismic-reflection data are insufficient to map sediment distribution and thickness in these extremely variable submarine-canyon environments.

To make these maps, water bottom and depth to base of the uppermost Pleistocene and Holocene sediment layer were mapped from seismic-reflection profiles (see fig. 1 on sheet 9; see also, sheet 8). The difference between the two horizons was exported for every shot point as XY coordinates (UTM zone 10) and two-way travel time (TWT). The thickness of the uppermost Pleistocene and Holocene unit (Maps B, D) was determined by applying a sound velocity of 1,600 m/sec to the TWT. 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 Monterey Bay and San Gregorio Fault Zones disrupt the sediment sequence in the region (Maps D, E on sheet 9). In addition, the thickness data points are dense along tracklines (about 1 m apart) and sparse between tracklines (1,000 to 1,250 m apart), resulting in minor contouring artifacts. To incorporate the effects 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 sediment-thickness maps (Maps B, D). Information for the depth to base of the uppermost Pleistocene and Holocene 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 uppermost Pleistocene and Holocene sediments on the continental shelf in the Offshore of Monterey map area ranges from 0 to 16 m (Map B on sheet 9). Mean sediment thickness on the shelf in the map area is 2.0 m, and the total sediment volume on the shelf is 281×10^6 m^3 (table 7–1). The thickest sediment in the map area (about 16 m) is found in a broad depression 2 km northwest of the northernmost tip of the Monterey peninsula, at water depths of about 75 to 85 m (see fig. 1 and Map B on sheet 9). Most of the shelf in the Offshore of Monterey map area consists of either exposed bedrock or bedrock overlain by a thin (less than 5 m) cover of sediment. The thinness of the sediment cover is the result of a combination of factors that include uplift of the Monterey peninsula, high wave energy, and limited sediment supply. Much of the sediment derived from the two largest watersheds in this area, the Salinas River and the Carmel River, is transported into the Monterey Canyon system (including Carmel Canyon) rapidly, with low residence time on the relatively narrow shelf.

Seven different informal “domains” of thickness of uppermost Pleistocene to Holocene sediment (table 7–1) are recognized on the regional sediment-thickness map (Map D on sheet 9), each with its own diverse set of geologic and (or) oceanographic controls. Again, data from within the Monterey Canyon system (including Carmel Canyon) were excluded from this analysis. Note that, on previously published maps of the Pigeon Point to southern Monterey Bay region (see, for example, Johnson and others, 2015), the first two domains listed below (Monterey shelf, Salinas River delta) were combined into the southern Monterey Bay domain.

(1) The Monterey shelf domain extends from Carmel and Monterey Canyons and the limit of California’s State Waters on the west to the shoreline along the Monterey peninsula and the southern part of Monterey Bay on the south and east. The domain includes all of the shelf within the Offshore of Monterey map area. Mean and maximum sediment thicknesses are 2.1 and 16 m, respectively. Small changes in sediment thickness over the shelf are largely controlled by irregular bedrock and, to a lesser degree, by faults, including the Monterey Bay Fault Zone (see Map E on sheet 9; see also, Greene, 1990).

(2) The Salinas River delta domain is bounded on the south by the sediment-poor Monterey shelf domain, on the east by the Monterey Bay shoreline, and on the north by Monterey Canyon. This domain consists of a large, shore-parallel, subaqueous delta that progrades across a thinly sediment-mantled bedrock shelf. Sediment thickness is as much as 32 m.

(3) The northern Monterey Bay domain is bounded on the south by Monterey Canyon, on the north and east by the Monterey Bay shoreline, and on the west by the limit of California's State Waters. The head of Monterey Canyon extends nearly to the shoreline, and the canyon forms a sediment trap that effectively separates the littoral- and shelf-sediment transport systems north and south of the canyon. The northern Monterey Bay domain is characterized by (a) a sediment-poor inner shelf cut by paleochannels of the San Lorenzo River, the Pajaro River, and Soquel Creek; (b) a midshelf depocenter that has sediment as thick as 32 m, much of which was deposited in a pre-LGM prograding delta and (or) shoreface complex and was preserved above a decrease in slope on the underlying unconformity; and (c) a midshelf to outer shelf zone in which sediment generally becomes progressively thinner in the offshore direction.

(4) The Davenport shelf domain extends from the northern limit of Monterey Bay northward to the southern margin of the Waddell Creek depocenter (to the north in the Waddell Creek delta domain). The Davenport shelf domain, as well as the three domains farther north, occupy a section of open, wave-dominated coast that is exposed to wave energy higher than that of the domains to the south in Monterey Bay and around Monterey peninsula. The Davenport shelf domain includes the Davenport depocenter, a prominent midshelf, shore-parallel depocenter present between Davenport and Santa Cruz that mostly consists of a lower, pre-LGM, clinoform-bearing unit of inferred prograding-shoreface origin. Sediment in this depocenter also is preserved in accommodation space linked to an offshore decrease in the slope of the underlying unconformity. Sediment thickness within the Davenport shelf domain decreases to both the northwest and southeast of this depocenter, owing to the presence of elevated bedrock and (or) the related absence of the lower clinoform-bearing unit.

(5) The Waddell Creek delta domain lies offshore of the mouth of the Waddell Creek coastal watershed, and it is connected to it by a submerged channel. The domain is both distinguished and delineated by the significant Waddell Creek depocenter (maximum sediment thickness of 19 m), which forms a moundlike delta that consists entirely of inferred post-LGM deposits whose primary source is Waddell Creek. Sediment thins both north and south of this moundlike delta; its preservation is attributable to its semiprotected (from erosive wave energy) location on the south flank of Point Año Nuevo.

(6) The Año Nuevo shelf domain lies offshore of Point Año Nuevo, from just north of Franklin Point on the north to just north of the mouth of Waddell Creek on the south. Bedrock exposures, which locally reach water depths of 45 m, cover a substantial part of this wave-exposed domain; in deeper waters farther offshore, sediment cover is relatively thin. Sediment thickness in this domain appears to be limited both by the lack of sediment supply (because of its distance from large coastal watersheds) and by the presence of uplifted bedrock, which is linked to a local zone of transpression in the San Gregorio Fault Zone (Weber, 1990). The uplift has raised this domain and exposed it to the high wave energy that is characteristic of this area (Storlazzi and Wingfield, 2005).

(7) The Pigeon Point shelf domain lies on the west flank of the Pigeon Point high (McCulloch, 1987). Sediment in the Pigeon Point shelf domain is thickest in a shore-parallel band that overlies a slope break in the underlying bedrock surface. Much of the sediment probably was derived from Pescadero Creek, a large coastal watershed that enters the Pacific Ocean about 3 km north of the Pigeon Point to southern Monterey Bay regional map area (see Maps C, D on sheet 9). The Pigeon Point shelf domain is transitional to the Pacifica-Pescadero shelf domain just north of it (see Watt and others, 2014).

Eittreim and others (2002, their fig. 15) showed an uppermost Pleistocene and Holocene sediment-thickness map that covers part of the area shown in Maps C and D on sheet 9 (from Point Año Nuevo in the north to Marina in the south). Their map combines three older investigations that cover the Davenport shelf (Mullins and others, 1985), Monterey Bay (Greene, 1977), and south-central Monterey Bay (Chin and others, 1988). These three investigations relied on analog seismic-reflection data collected in the 1970s and early 1980s, and they predate the availability of both digital high-resolution seismic-reflection data (see sheet 8) and high-resolution bathymetry (see, for example, sheets 1, 2), both of which provided essential input to the development of the maps shown on sheet 9. Although the sediment-depth and -thickness patterns are grossly similar between the two generations of maps, the accuracy and level of detail in the newer maps is significantly higher.

Table 7–1. Area, sediment-thickness, and sediment-volume data for California's State Waters in Pigeon Point to southern Monterey Bay region (domains 1–7), as well as in Offshore of Monterey map area.

Regional sediment-thickness domains in Pigeon Point to southern Monterey Bay region			
	Area (km^2)	**Mean sediment thickness (m)**	**Sediment volume (10^6 m^3)**
Entire Pigeon Point to southern Monterey Bay region	862	6.6	5,663
(1) Monterey shelf	159	2.1	334
(2) Salinas River delta	107	11.3	1,207
(3) Northern Monterey Bay	307	6.7	2,065
(4) Davenport shelf	134	8.3	1,113
(5) Waddell Creek delta	29	7.8	224
(6) Año Nuevo shelf	58	2.6	154
(7) Pigeon Point shelf	68	8.8	598
Sediment thicknesses in Offshore of Monterey map area			
Entire Offshore of Monterey map area	142	2.0	281

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

By Stephen R. Hartwell, Samuel Y. Johnson, Clifton W. Davenport, and Janet T. Watt

Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Monterey map area from approximate Mean High Water (MHW) across the continental shelf, as well as in Carmel Canyon to a water depth of about 1,600 m. This map area includes much of southern Monterey Bay, as well as open coastal waters west of the Monterey peninsula to beyond the limit of California's State Waters (note that the California's State Waters limit, which generally is 3 nautical miles [5.6 km] from shore, extends farther offshore (as much as 12 nautical miles) between Santa Cruz and Monterey, so that it encompasses all of Monterey Bay; see figs. 1–1, 1–2). The shoreline, which is from the National Oceanic and Atmospheric Administration's (NOAA's) Shoreline Data Explorer, is based on their analysis of lidar data (National Geodetic Survey, 2015). 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 (Wong and Eittreim, 2002; Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8). Aerial photographs taken in multiple years were used to map the nearshore area (0 to 10 m water depth) and to link the offshore and onshore geology.

The onshore geology was compiled from Clark and others (1997) and Wagner and others (2002); unit ages, which are from these sources, reflect local stratigraphic relations. In addition, some Quaternary units were modified by C.W. Davenport on the basis of analysis of 2009 lidar imagery.

The offshore part of the map area contains two geomorphic features, (1) the continental shelf, and (2) Carmel Canyon and its tributaries (part of the "Monterey Canyon system" of Greene and others [2002]). Most of the relatively flat continental shelf in the Offshore of Monterey map area consists of either exposed bedrock or bedrock overlain by a thin (less than 5 m) cover of sediment. The thickest sediment in the map area (about 16 m) is found in a broad depression about 2 km north of the northernmost tip of the Monterey peninsula, at water depths of about 75 to 85 m (see Map B on sheet 9). Inner shelf to midshelf and nearshore deposits are mostly sand (Qms); coarse sand and gravel (Qmsc) is present in the midshelf area about 2 km offshore of Seaside. Unit Qmsf, which lies offshore of unit Qms in the midshelf to outer shelf area (water depths of 65 to 150 m), primarily consists of mud and muddy sand, and it commonly is extensively bioturbated.

Unit Qmsd typically is mapped as erosional lags in scour depressions (see, for example, Cacchione and others, 1984) that are bounded by relatively sharp or, less commonly, diffuse contacts with the horizontal sand sheets of unit Qms. These depressions typically are irregular to lenticular and a few tens of centimeters deep, and they range in size from a few tens of square meters to as much as 2,400,000 m^2. They most commonly are found at water depths that range from about 15 to 90 m. 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 low sediment supply from rivers and also to significant erosion and offshore transport of sediment during large northwest winter swells. Such features have been referred to as "rippled scour depressions" (see, for example, Cacchione and others, 1984) or "sorted bedforms" (see, for example, Goff and others, 2005; Trembanis and Hume, 2011). Although the general areas in which both unit Qmsd scour depressions and surrounding Qms sand sheets are found are not likely to change substantially, the boundaries of the unit(s) likely are ephemeral, changing seasonally and during significant storm events.

Sea level has risen about 125 to 130 m over about the last 21,000 years (see, for example, Stanford and others, 2011), leading to broadening of the continental shelf, progressive eastward migration of the shoreline, and associated transgressive erosion and deposition. A submerged shoreline along the flank of Carmel Canyon (water depths of 80 to 90 m) represents a relative sea-level stillstand, indicating that sea-level rise was not steady. Associated map units include a wave-cut platform (Qwp) and an adjacent riser (Qwpr).

Bedrock outcrops on the shelf include the Cretaceous granitic rocks of Monterey (Kgr); the Paleocene Carmelo Formation (Tc; Bowen, 1965); the Oligocene volcanic rocks (Tvb), consisting of basaltic andesite; the Miocene Monterey Formation (Tm); and the upper Miocene and Pliocene Purisima Formation (Tp) (Eittreim and others, 2002; Wagner and others, 2002). In areas where rocks of the Carmelo Formation and the Oligocene volcanic rocks cannot be confidently divided, unit Tu is mapped. Unit Kgr notably is characterized by high backscatter (sheet 3) and its rough, massive, and fractured seafloor texture. In contrast, the less indurated Neogene sedimentary rocks (most notably units Tm and Tp) form lower relief outcrops that commonly have “ribbed” morphology, which reflects the differential hardness (and, hence, erodibility) of sedimentary layers. Several of these bedrock units are in places overlain by a thin (less than 1 m?) veneer of sediment, recognized on the basis of high backscatter, flat relief, continuity with moderate- to high-relief outcrops, and (in some cases) high-resolution seismic-reflection profiles; these areas, which are mapped as composite units (for example, Qms/Kgr, Qmsf/Tp) are interpreted as ephemeral sediment layers that may or may not be continuously present, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term climate cycles.

The shelf northeast and north of the Monterey peninsula in the map area is cut by the diffuse zone of northwest-striking, steeply dipping to vertical faults of the Monterey Bay Fault Zone. This fault zone, originally mapped by Greene (1977, 1990), extends about 45 km across outer Monterey Bay (see Map E on sheet 9). Fault strands within the Monterey Bay Fault Zone are mapped with high-resolution seismic-reflection profiles (see sheet 8). Seismic-reflection profiles in the map area that traverse this diffuse zone cross as many as five faults over a width of about 4 to 5 km (see, for example, figs. 3, 5 on sheet 8). The Monterey Bay Fault Zone lacks a continuous “master fault” along which deformation is concentrated. Fault strands are as long as about 20 km (on the basis of mapping outside the map area), but most strands are only about 2 to 7 km long. Faults in this diffuse zone cut through Neogene bedrock, and they locally appear to have minimally disrupted the overlying inferred Quaternary sediments. The presence of warped reflections along some fault strands suggests that both vertical and strike-slip offset may have occurred. To the south-southeast, the Monterey Bay Fault Zone connects with the Navy, Chupines, Seaside, and Ord Terrace Faults onland (Clark and others, 1997; Wagner and others, 2002).

Carmel Canyon, a relatively straight, northwest-trending arm of the Monterey Canyon system that cuts through the southwestern part of the Offshore of Monterey map area, has three heads (Greene and others, 2002). At the south edge of the map area, two heads extend to the east and northeast into Carmel Bay; south of the map area, the third head extends southeast along the main canyon axis for about 3 km beyond the confluence with the heads in Carmel Bay. Sandy canyon-head channel deposits (Qchc) are mapped at the head of the northeast-trending arm of Carmel Canyon, in Carmel Bay.

Active Carmel Canyon channel fill is mapped as three distinct units: unit Qcpcf, which is mapped in upper Carmel Canyon, is characterized by sandy, crescentic bedforms; unit Qccf1, which is mapped in curvilinear tributaries on the north and east flanks of Carmel Canyon, consists of gravel and minor bedrock outcrops and landslide deposits; unit Qccf2, which is mapped in primary Carmel Canyon channels, consists of sand and gravel that locally forms crescentic bedforms, and it also includes small bedrock outcrops and landslide deposits. Sand and mud deposited on a bench immediately adjacent to the axial channel of Carmel Canyon is mapped as unit Qcb; although this unit is present only in a small part of the map area, it is more widespread in Monterey Canyon (Maier and others, 2016) to the north, and it also is more extensive in the parts of Carmel Canyon that are south of the map area.

Carmel Canyon walls that are relatively smooth generally are covered by muddy Quaternary sediments (Qcw), whereas steeper and rougher segments of the canyon walls commonly contain exposures of bedrock. Outcrops of the Purisima Formation are found in the upper canyon walls (Tpcw) in the northwestern part of the map area. Older, underlying bedrock units exposed at greater depths along canyon walls (Greene, 1977; Greene and others, 1991; Wong and Eittreim, 2002) include the Miocene Monterey Formation (Tmcw) and the Cretaceous granitic rocks of Monterey (Kgrcw). The relatively smooth, flat area in the southwest corner of the map area forms a bathymetric divide between Carmel Canyon to the east and Point Lobos canyon (an informally named submarine canyon west of the map area; see fig. 1–1) to the west, and it is inferred to be covered by mud and minimal sand (Qmscp).

Carmel Canyon roughly aligns with, and is structurally controlled by, the San Gregorio Fault Zone (Greene and others, 1991), an important structure in the distributed transform boundary between the North American and Pacific plates (see, for example, Dickinson and others, 2005). This fault zone is part of a regional fault 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; Johnson and Watt, 2012) to Bolinas and Point Reyes in the north (Bruns and others, 2002; Ryan and others, 2008). The San Gregorio Fault Zone in the map area is part of a 90-km-long offshore segment that extends northward from Point Sur (about 25 km south of the map area), across outer Monterey Bay to Point Año Nuevo (about 50 km north of the map area) (see sheet 9; see also, Weber and Lajoie, 1980; Brabb and others, 1998; Wagner and others, 2002). High-resolution seismic-reflection data collected across the canyon do not clearly image the San Gregorio Fault Zone, largely owing to its significant depth and steep canyon walls. Accordingly, we have mapped the 1,000- to 1,300-m-wide fault zone largely on the basis of the presence of prominent, lengthy geomorphic lineaments (see sheets 1, 2), as well as the geomorphic and lithologic contrasts across the fault (see sheet 10). Following Greene and others (2002), we map the relatively straight-sloping drainage channels and slumps that lightly dissect the east wall of Carmel Canyon, which is underlain by the Cretaceous granitic rocks of Monterey (Kgrcw). In contrast, the steep cliffs along the west wall of the canyon are underlain by a mix of the Miocene Monterey Formation (here, mapped as Tmcw) and, west of the map area, Cretaceous sedimentary rocks (Greene, 1977; Greene and others, 1991; Eittreim and others, 2002; Wong and Eittreim, 2002).

The relative proportions of all offshore map units are shown in table 8–1. These areas are calculated from “flat” GIS polygons and do not account for sloped surface areas. Using this standard technique, areas and percentages for units that contain steep canyon walls are underestimated, whereas areas and percentages for flatter regions (for example, shelf units) are overestimated.

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

Map Unit	Area (m^2)	Area (m^2)	Percent of total area
Marine shelf sedimentary units			
af	49,947	0.0	0.0
Qms	79,625,410	79.6	29.7
Qmsd	8,081,663	8.1	3.0
Qmsc	942,202	0.9	0.4
Qmsf	18,252,877	18.3	6.8
Qwp	13,423	0.0	0.0
Qwpr	5,133	0.0	0.0
Total, sedimentary units	106,970,655	107	39.9
Marine shelf bedrock and (or) shallow-bedrock units			
Qms/Tp	676,353	0.7	0.3
Qmsf/Tp	1,110,441	1.1	0.4
Qms/Tm	88,578	0.1	0.0
Qms/Tc	97,611	0.1	0.0
Qms/Tvb	728	0.0	0.0
Qms/Tu	141,799	0.1	0.1
Qms/Kgr	3,211,075	3.2	1.2
Tp	10,750,571	10.8	4.0
Tm	3,885,186	3.9	1.5
Tc	900,646	0.9	0.3
Tvb	350,227	0.4	0.1
Tu	1,460,914	1.5	0.5
Kgr	40,653,098	40.7	15.2
Total, bedrock units	62,650,875	63	23.4
Marine submarine-canyon sedimentary units			
Qchc	117,434	0.1	0.0
Qcpcf	452,333	0.5	0.2
Qccf2	4,453,735	4.5	1.7
Qccf1	628,918	0.6	0.2
Qcb	18,678	0.0	0.0
Qmscp	8,389,367	8.4	3.1
Qcw	45,648,184	45.6	17.0
Total, canyon sedimentary units	59,708,649	60	22.3
Marine submarine-canyon bedrock units			
Tpcw	940,198	0.9	0.4
Tmcw	7,929,196	7.9	3.0
Kgrcw	29,742,655	29.7	11.1
Total, canyon bedrock units	38,612,048	38.6	14.4
Total, Offshore of Monterey map area	267,942,227	267.9	100.0

DESCRIPTION OF MAP UNITS

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Note that, where older units (typically, bedrock) are overlain by thin (<1 m thick) unconsolidated Quaternary deposits, composite units are mapped. These composite units, which are shown with gray or white 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)]

NEARSHORE, SHELF, AND CANYON RIM

af **Artificial fill (late Holocene)**—Rock, sand, and mud; placed and (or) dredged; associated with Monterey Harbor

Qms **Marine nearshore and shelf deposits (late Holocene)**—Predominantly sand; ripple marks common

Qmsd **Marine shelf scour depressions (late Holocene)**—Inferred to be coarse sand and possibly gravel; consists of irregular, arcuate scour depressions that are found inside Monterey Bay and both north and west of Monterey peninsula. Depressions are typically 15 to 50 cm deep, and they have sharp to diffuse boundaries. 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) likely are ephemeral, changing during significant storm events

Qmsc **Coarse-grained marine nearshore and shelf deposits (late Holocene)**—Predominantly coarse sand to gravel; found primarily about 2 km offshore of Sand City; recognized on basis of high backscatter and flat relief

Qmsf **Fine-grained marine shelf deposits (late Holocene)**—Predominantly mud, very fine sand, and silt; commonly bioturbated

Qwp **Submerged wave-cut platform, about 80 to 90 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Present only on north flank of tributary of Carmel Canyon, south of Monterey peninsula. Platform is as wide as 130 m and can be continuously traced laterally for about 150 m; bounded upslope by paleoshoreline angle (Kern, 1977) and unit platform riser (Qwpr). Platform is inferred to have been formed by wavecutting, in periods of relative sea-level stillstand during overall sea-level rise following Last Glacial Maximum (Stanford and others, 2011)

Qwpr **Submerged wave-cut platform riser, base about 80 to 90 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Present only on north flank of tributary of Carmel Canyon, south of Monterey peninsula. Upper contact is continental shelf, whereas lower contact is paleoshoreline angle (Kern, 1977). Represents paleo–sea cliff or onshore slope associated with development of wave-cut platform (Qwp)

Tp **Purisima Formation (Pliocene and late Miocene)**—Thick-bedded, tuffaceous and diatomaceous siltstone that contains thick interbeds of fine-grained sandstone and mudstone. Age is based on biostratigraphic and geochronologic data summarized by Powell and others (2007). Stippled areas (composite units Qms/Tp and Qmsf/Tp) indicate where thin sheets of Qms or Qmsf overlie unit

Tm **Monterey Formation (Miocene)**—Porcelaneous shale, chert, and mudstone, calcareous claystone, and small amounts of siltstone and sandstone. Stippled areas (composite unit Qms/Tm) indicate where thin sheets of Qms overlie unit

Tvb **Volcanic rocks (Oligocene)**—Basaltic andesite flows and flow breccias. Stippled areas (composite unit Qms/Tvb) indicate where thin sheets of Qms overlie unit

Tu **Sedimentary and (or) volcanic rocks, undivided (Oligocene to Paleocene)**—May consist of Oligocene volcanic rocks (Tvb) or rocks of the Carmelo Formation (Tc). Stippled areas (composite unit Qms/Tu) indicate where thin sheets of Qms overlie unit

Tc **Carmelo Formation (Paleocene)**—Thin- to thick-bedded and graded arkosic sandstone that contains interbedded siltstone and pebble and cobble conglomerate. Stippled areas (composite unit Qms/Tc) indicate where thin sheets of Qms overlie unit

Kgr **Granitic rocks of Monterey (Cretaceous)**—Mainly porphyritic granodiorite (Ross, 1976). Stippled areas (composite unit Qms/Kgr) indicate where thin sheets of Qms overlie unit

SUBMARINE CANYON

Channels

Qchc **Submarine-canyon-head channel deposits (late Holocene)**—Primarily sand; mapped at uppermost part of northeast-trending head of Carmel Canyon in Carmel Bay

Qcpcf **Proximal active submarine-canyon axial-channel fill (late Holocene)**—Primarily sand; found in upper Carmel Canyon; characterized by crescent-shaped bedforms

Qccf2 **Active submarine-canyon axial-channel fill (late Holocene)**—Sand and gravel; locally forms crescent-shaped bedforms; minor bedrock outcrops and landslide deposits; mapped in main Carmel Canyon channel

Qccf1 **Active tributary-submarine-canyon channel fill (late Holocene)**—Sand and gravel; minor bedrock outcrops and landslide deposits; in curvilinear tributaries on north and east flanks of Carmel Canyon

Walls

Qcb **Submarine-canyon inner bench deposits (Holocene)**—Mud and sand; areas of lower gradient adjacent to axial channel that accumulate dominantly fine-grained sediments

Qmscp **Submarine-canyon platform deposits (Holocene and Pleistocene)**—Mud and minimal sand; relatively smooth areas of lower gradient on crests of bathymetric divide between Carmel Canyon and Point Lobos canyon (see fig. 1–1)

Qcw **Submarine-canyon-wall deposits (Holocene and Pleistocene)**—Inferred to be draped by marine and hemipelagic sediments; may contain bedrock outcrops and landslide deposits too small to show at map scale; distinguished from units Tpcw, Tmcw, and Kgrcw largely on basis of acoustic backscatter (see sheet 3)

Tpcw **Purisima Formation (Pliocene and late Miocene)**—Marine sandstone, siltstone, and mudstone; found within submarine-canyon walls; distinguished from unit Qcw largely on basis of acoustic backscatter (see sheet 3)

Tmcw **Monterey Formation (Miocene)**—Porcelaneous shale, chert, and mudstone; calcareous claystone; and small amounts of siltstone and sandstone; found within submarine-canyon walls

Kgrcw **Granitic rocks of Monterey (Cretaceous)**—Found within submarine-canyon walls

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units compiled from Clark and others (1997) and Wagner and others (2002); unit ages, which are from these sources, reflect local stratigraphic relations. In addition, some Quaternary units modified by C.W. Davenport on basis of analysis of 2009 lidar imagery]

af **Artificial fill (late Holocene)**—Heterogeneous mixture of artificially deposited material; ranges from well-compacted sand and silt to poorly compacted sediment high in organic content

alf **Artificial fill, jetties, and levees (late Holocene)**—Jetties, entrance to Monterey Harbor, and levees around lakes

acf **Artificial fill in stream channels (late Holocene)**—Material placed in historically active stream channels

Qc **Active stream-channel deposits (late Holocene)**—Active stream channels that contain unconsolidated sand, silt, and gravel deposits

Qbs **Beach-sand deposits (late Holocene)**—Fine to very-coarse sand; forms active beaches along coast; may form veneer over bedrock platform. Locally, includes dune-sand deposits too small to delineate at map scale

Qyd **Dune-sand deposits (Holocene)**—Very well-sorted, fine to medium sand; forms active dunes along coast

Qal **Alluvial deposits, undivided (Holocene)**—Alluvium deposited adjacent to active stream channels, including flood-plain deposits of Wagner and others (2002). Locally, may include stream-terrace and channel deposits too small to delineate at map scale

Qb **Basin deposits (Holocene)**—Unconsolidated, fine-grained sediment; deposited in low-energy environments that include estuaries, lagoons, marsh-filled sloughs, and lakes

Qe **Estuarine deposits (Holocene)**—Unconsolidated silt and clay and interbedded, organic-rich layers; deposited in low-energy environments near mouth of Carmel River

Qyf **Alluvial fan deposits (Holocene)**—Unconsolidated, heterogeneous layers of sand, silt, and gravel; relatively undissected; deposited by streams emanating from canyons onto alluvial plains; identified primarily by fan morphology and topographic expression

Qyt **Stream-terrace deposits (Holocene)**—Sand, gravel, silt, and minor clay; overlies relatively flat platforms that are elevated slightly above, and are adjacent to, alluvial deposits or stream channels

Qcl **Colluvium (Holocene)**—Loose to firm, unsorted sand, silt, clay, gravel, rock debris, and organic material, in varying proportions; typically mapped in hillside swales and narrow immature drainages; may contain numerous small landslide deposits and (or) alluvial fans

Qd **Dune-sand deposits (Holocene and Pleistocene)**—Very well-sorted, fine to medium sand; forms stabilized dunes of uncertain age near coast

Qf **Alluvial fan deposits (Holocene and Pleistocene)**—Mapped either where older age is indicated by greater degree of dissection, or at elevations higher, than that of adjacent Holocene alluvial fans

Qt **Stream-terrace deposits (Holocene to Pleistocene)**—Sand, gravel, silt, and minor clay of uncertain age, on relatively flat, elevated surfaces above stream channels

Qls **Landslide deposits (Holocene and Pleistocene)**—Weathered and disintegrated rocks and soil; physically weathered; queried where uncertain

Qmt **Marine-terrace deposits, undivided (Pleistocene)**—Semiconsolidated sand and local gravel deposits, on uplifted marine-abrasion platforms along coast; locally, may include fluvial and (or) colluvial deposits too small to delineate at map scale; queried where uncertain

Qoa **Older alluvium (Pleistocene)**—Moderately to deeply dissected, undifferentiated alluvial deposits; commonly mapped on gently rolling hills where little to none of original planar alluvial surface is preserved; queried where uncertain

Qof **Alluvial fan deposits (Pleistocene)**—Discontinuous or highly dissected deposits of semiconsolidated, moderately to poorly sorted layers of fluvial silty clay, silt, sand, and gravel; deposited adjacent to mountains

Qot **Stream-terrace deposits (Pleistocene)**—Sand, gravel, silt, and minor clay; underlies relatively flat surfaces elevated well above stream channels

Qod **Older dune-sand deposits (Pleistocene)**—Very well-sorted, fine to medium sand; forms extensive coastal dune fields; queried where uncertain

Qae **Aromas Sand, eolian lithofacies (early Pleistocene)**—Moderately well-sorted, wind-blown sand

QTc **Continental deposits, undivided (Pleistocene and Pliocene?)**—Semiconsolidated, fine-grained, oxidized sand and silt; may represent highly weathered eolian sediment

Tsm **Santa Margarita Sandstone (late Miocene)**—Marine and brackish-marine, yellowish-gray to white, friable, fine- to medium-grained arkosic sandstone; queried where uncertain

Tm **Monterey Formation (Miocene)**—Pale-orange to white, porcelaneous shale that has chert, mudstone, calcareous claystone, and small amounts of siltstone and sandstone near base

Tus **Unnamed sandstone (early Miocene)**—Dark-yellowish-orange, poorly to well sorted arkosic sandstone that has conglomerate beds near base; queried where uncertain

Tvb **Volcanic rocks (Oligocene)**—Thin flows and flow breccias of basaltic andesite

Tc **Carmelo Formation (Paleocene)**—Thin- to thick-bedded, graded arkosic sandstone interbedded with pebble and cobble conglomerate

Kgd **Granodiorite of Monterey (Cretaceous)**—Porphyritic, gray, medium-grained granodiorite that contains orthoclase phenocrysts of various sizes (Ross, 1976); queried where uncertain

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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.

Bowen, O.E., Jr., 1965, Stratigraphy, structure, and oil possibilities in Monterey and Salinas quadrangles, California: Bakersfield, Calif., American Association of Petroleum Geologists, Pacific Section, 40th annual meeting, p. 48–67.

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 Farallones as inferred 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 Wildlife, 2008, California Marine Life Protection Act master plan for marine protected areas—Revised draft: California Department of Fish and Wildlife [formerly California Department of Fish and Game], available at https://www.wildlife.ca.gov/Conservation/Marine/MPAs/Master-Plan.

California State University, Monterey Bay, Seafloor Mapping Lab, 2015, Monterey Bay data: California State University, Monterey Bay, Seafloor Mapping Lab Data Library, accessed October 2015 at http://seafloor.otterlabs.org/SFMLwebDATA_SURVEYMAP.htm.

Chin, J.L., Clifton, H.E., and Mullins, H.T., 1988, Seismic stratigraphy and late Quaternary shelf history, south-central Monterey Bay, California: Marine Geology, v. 81, p. 137–157.

Clark, J.C., Dupré, W.R., and Rosenberg, L.L., 1997, Geologic map of the Monterey and Seaside 7.5-minute quadrangles, Monterey County, California—A digital database: U.S. Geological Survey Open-File Report 97–30, 2 sheets, scale 1:24,000, available at http://pubs.usgs.gov/of/1997/of97-030/.

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 pubs/615_habitat_mapping_workshop/Individual Chapters High-Res/Ch13 Cochrane.pdf.

Cochrane, G.R., Conrad, J.E., Reid, J.A., Fangman, S., and Golden, N., 2005, 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, W.S., 1967, Coastal dunes of California: Geological Society of America Memoir 104, 131 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.

Eittreim, S.L., Anima, R.J., and Stevenson, A.J., 2002, Seafloor geology of the Monterey Bay area continental shelf: Marine Geology, vol. 181, p. 3–34.

Goff, J.A., Mayer, L.A., Traykovski, P., Buynevich, I., Wilkens, R., Raymond, R., Glang, G., Evans, R.L., Olson, H., and Jenkins, C., 2005, Detailed investigations of sorted bedforms or "rippled scour depressions," within the Martha's Vineyard Coastal Observatory, Massachusetts: Continental Shelf Research, v. 25, p. 461–484, doi:10.1016/j.csr.2004.09.019.

Greene, H.G., 1977, Geology of the Monterey Bay region: U.S. Geological Survey Open-File Report 77–718, 347 p., available at https://pubs.er.usgs.gov/publication/ofr77718.

Greene, H.G., 1990, Regional tectonics and structural evolution of the Monterey Bay region, central California, *in* Garrison, R.E., Greene, H.G., Hicks, K.R., Weber, G.E., and Wright, T.L., eds., Geology and tectonics of the central California coastal region, San Francisco to Monterey: American Association of Petroleum Geologists, Pacific Section, Guidebook GB67, p. 31–56.

Greene, H.G., and Bizzarro, J.J., 2003, Essential fish habitat characterization and mapping of the California continental margin: Final Report to Pacific States Marine Fisheries Commission, CFDA #11-454, 14 p., available at http://marinehabitat.psmfc.org/files/source_docs/EFH_report_with_Appendices.pdf.

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., Clarke, S.H., and Kennedy, M.P., 1991, Tectonic evolution of submarine canyons along the California continental margin—From shoreline to abyss, *in* Osborne, R.H., ed., Society for Sedimentary Geology, Special Publication no. 46, p. 231–248.

Greene, H.G., Maher, N.M., and Paull, C.K., 2002, Physiography of the Monterey Bay National Marine Sanctuary and implications about continental margin development: Marine Geology, v. 181, p. 55–82.

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., and Reid, D.R., 2007, National assessment of shoreline change part 4—Historical coastal cliff retreat along the California Coast: U.S. Geological Survey Open-File Report 2007–1133, 51 p., available at http://pubs.usgs.gov/of/2007/1133/.

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.

Johnson, S.Y., Hartwell, S.R., Watt, J.T., Sliter, R.W., and Maier, K.L., 2015, Local (Offshore of Scott Creek map area) and regional (offshore from Pigeon Point to southern Monterey Bay) shallow-subsurface geology and structure, California, *sheet 9 in* Cochrane, G.R., Dartnell, P., Johnson, S.Y., Greene, H.G., Erdey, M.D., Dieter, B.E., Golden, N.E., Endris, C.A., Hartwell, S.R., Kvitek, R.G., Davenport, C.W., Watt, J.T., Krigsman, L.M., Ritchie, A.C., Sliter, R.W., Finlayson, D.P., and Maier, K.L. (G.R. Cochrane and S.A. Cochran, eds.), California State Waters Map Series—Offshore of Scott Creek, California: U.S. Geological Survey Open-File Report 2015–1191, pamphlet 40 p., 10 sheets, scale 1:24,000, http://dx.doi.org/10.3133/ofr20151191.

Johnson, S.Y., and Watt, J.T., 2012, Influence of fault trend, bends, and convergence on shallow structure and geomorphology of the Hosgri strike-slip fault, offshore Central California: Geosphere, v. 8, p. 1,632–1,656, doi:10.1130/GES00830.1.

Kern, J.P., 1977, Origin and history of upper Pleistocene marine terraces, San Diego, California: Geological Society of America Bulletin, v. 88, p. 1,553–1,566.

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://www.opc.ca.gov/webmaster/ftp/project_pages/mapping/2005 FINAL mapping report April 2006.pdf.

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.

Maier, K.L., Hartwell, S.R., Johnson, S.Y., Davenport, C.W., and Greene, H.G., 2016, Offshore and onshore geology and geomorphology, Monterey Canyon and Vicinity map area, California, *sheet 10 in* Dartnell, P., Maier, K.L., Erdey, M.D., Dieter, B.E., Golden, N.E., Johnson, S.Y., Hartwell, S.R., Cochrane, G.R., Ritchie, A.C., Finlayson, D.P., Kvitek, R.G., Sliter, R.W., Greene, H.G., Davenport, C.W., Endris, C.A., and Krigsman, L.M. (P. Dartnell and S.A. Cochran, eds.), California State Waters Map Series—Monterey Canyon and Vicinity: U.S. Geological Survey Open-File Report 2016–1072, pamphlet 48 p., 10 sheets, scale 1:24,000, http://dx.doi.org/10.3133/ofr20161072.

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.
Mullins, H.T., Nagel, D.K., and Dominguez, L.L., 1985, Tectonic and eustatic controls of late Quaternary shelf sedimentation along the central California (Santa Cruz) continental margin—High-resolution seismic stratigraphic evidence: Sedimentary Geology, v. 45, p. 327–347.
Murray, A.B., and Thieler, E.R., 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.
National Centers for Environmental Information, 2015, Bathymetric data viewer: National Oceanic and Atmospheric Administration, National Centers for Environmental Information (formerly National Geophysical Data Center), Bathymetric data viewer and database, accessed October 10, 2015, at http://www.ngdc.noaa.gov/mgg/bathymetry/.
National Geodetic Survey, 2015, NOAA Shoreline Data Explorer: National Oceanic and Atmospheric Administration, National Geodetic Survey data viewer and database, accessed May 1, 2015, at http://www.ngs.noaa.gov/NSDE/.
National Oceanic and Atmospheric Administration, 2013, 2013 NOAA Coastal California TopoBathy Merge Project: National Oceanic and Atmospheric Administration, National Centers for Environmental Information database, accessed October 2015 at http://www.ngdc.noaa.gov/docucomp/page?xml=NOAA/NESDIS/NGDC/MGG/Lidar/iso/xml/2013_CA_TopoBathy_m2612.xml&view=getDataView&header=none.
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.
Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p., available at http://dx.doi.org/10.3133/ofr20141091.
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.
Powell, C.L., II, Barron, J.A., Sarna-Wojcicki, A.M., Clark, J.C., Perry, F.A., Brabb, E.E., and Fleck, R.J., 2007, Age, stratigraphy, and correlations of the late Neogene Purisima Formation, central California Coast Ranges: U.S. Geological Survey Professional Paper 1740, 32 p., available at http://pubs.usgs.gov/pp/2007/1740/.
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/.
Ross, D.C., 1976, Reconnaissance geologic map of pre-Cenozoic basement rocks, northern Santa Lucia Range, Monterey County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–750, 7 p., 2 plates, scale 1:125,000, available at https://pubs.er.usgs.gov/publication/mf750.

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.

Sliter, R.W., Johnson, S.Y., Watt, J.T., Scheirer, D.S., Allwardt, P., and Triezenberg, P.J., 2013, High-resolution seismic-reflection and marine-magnetic data from offshore central California—San Gregorio to Point Sur: U.S. Geological Survey Open-File Report 2013–1071, available at http://pubs.usgs.gov/of/2013/1071/.

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.

Spudich, P., ed., 1996, The Loma Prieta, California, earthquake of October 17, 1989—Main shock characteristics: U.S. Geological Survey Professional Paper 1550–A, 297 p., available at http://pubs.usgs.gov/pp/pp1550/pp1550a/.

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., and Wingfield, D.K., 2005, Spatial and temporal variations in oceanographic and meteorologic forcing along the central California coast, 1980–2002: U.S. Geological Survey Scientific Investigations Report 2005–5085, 39 p., available at http://pubs.usgs.gov/sir/2005/5085/.

Tinker, M.T., Doak, D.F., and Estes, J.A., 2008, Using demography and movement behavior to predict range expansion of the southern sea otter: Ecological Applications, v. 18, p. 1,781–1,794, doi:10.1890/07-0735.1.

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, doi:10.1007/s00367-010-0225-8.

Triezenberg, P.J., Hart, P.E., and Childs, J.R., 2016, National Archive of Marine Seismic Surveys (NAMSS)—A USGS data website of marine seismic reflection data within the U.S. Exclusive Economic Zone (EEZ): U.S. Geological Survey data release, accessed June 29, 2015, at http://dx.doi.org/10.5066/F7930R7P [formerly U.S. Geological Survey's National Archive of Marine Seismic Surveys database, available 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/.

Wagner, D.L., Greene, H.G., Saucedo, G.J., and Pridmore, C.L., 2002, Geologic map of the Monterey 30' × 60' quadrangle and adjacent areas, California: California Geological Survey Regional Geologic Map Series, scale 1:100,000, available at http://www.quake.ca.gov/gmaps/RGM/monterey/monterey.html.

Watt, J.T., Hartwell, S.R., Johnson, S.Y., Sliter, R.W., Phillips, E.L., Ross, S.L., and Chin, J.L., 2014, Local (Offshore of San Gregorio map area) and regional (offshore from Bolinas to Pescadero) shallow-subsurface geology and structure, California, *sheet 9 in* Cochrane, G.R., Dartnell, P., Greene, H.G., Watt, J.T., Golden, N.E., Endris, C.A., Phillips, E.L., Hartwell, S.R., Johnson, S.Y., Kvitek, R.G., Erdey, M.D., Bretz, C.K., Manson, M.W., Sliter, R.W., Ross, S.L., Dieter, B.E., and Chin, J.L. (G.R. Cochrane and S.A. Cochran, eds.), California State Waters Map Series—Offshore of San Gregorio, California: U.S. Geological Survey Scientific Investigations Map 3306, pamphlet 38 p., 10 sheets, scale 1:24,000, available at http://dx.doi.org/10.3133/sim3306.

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, 3 sheets, scale 1:24,000, available at http://pubs.er.usgs.gov/publication/ofr80907.

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

Wong, F.L., and Eittreim, S.L., 2002, Continental shelf GIS for the Monterey Bay National Marine Sanctuary: Marine Geology, v. 181, p. 317–321 and CDROM.

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/.

Wright, D.J., Pendleton, M., Boulware, J., Walbridge, S., Gerlt, B., Eslinger, D., Sampson, D., and Huntley, E., 2012, ArcGIS Benthic Terrain Modeler (BTM), v. 3.0: Environmental Systems Research Institute and NOAA Coastal Services Center, Massachusetts Office of Coastal Zone Management, accessed February 1, 2013, at http://esriurl.com/5754.