California State Waters Map Series—Monterey Canyon and Vicinity, California

By Peter Dartnell, Katherine L. Maier, Mercedes D. Erdey, Bryan E. Dieter, Nadine E. Golden, Samuel Y. Johnson,
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(Peter Dartnell and Susan A. Cochran, editors)

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California State Waters Map Series—Monterey Canyon and Vicinity, California

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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 potential 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

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is published as a PDF file. Geographic information system (GIS) files that contain both ESRI[6] ArcGIS raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed March 5, 2014).

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.

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[6] Environmental Systems Research Institute, Inc.

Chapter 1. Introduction

By Peter Dartnell

Regional Setting

The map area offshore of Moss Landing, California, which includes the submarine Monterey Canyon and, thus, is referred to herein as the "Monterey Canyon and Vicinity" map area (figs. 1–1, 1–2), lies within Monterey Bay in central California. Monterey Bay is one of the largest embayments along the west coast of the United States, spanning 36 km from its northern to southern tips (in Santa Cruz and Monterey, respectively) and 20 km along its central axis. Not only does it contain one of the broadest sections of continental shelf along California's coast, it also contains Monterey Canyon, one of the largest and deepest submarine canyons in the world. 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 coastal area within the Monterey Canyon and Vicinity map area is lightly populated, compared to other parts of the California coast. The community of Moss Landing, which has a population of only 204 people (City-Data.com, 2014), is located on the coast; its harbor hosts the largest commercial fishing fleet in Monterey Bay. Fertile lowlands of the Salinas River and Pajaro River valleys largely occupy the inland part of the map area, and land use is primarily agricultural. The map area also includes the northern part of the city of Marina (population, about 20,000), which lies along the coast near the south edge of the map area; the city of Castroville (population, about 6,500) lies about 5 km inland. Castroville calls itself the "artichoke center of the world," and strawberries are an important secondary crop.

This offshore part of the map area lies completely within the Monterey Bay National Marine Sanctuary, one of the nation's largest marine sanctuaries, designated in 1992. The map area also includes Portuguese Ledge State Marine Conservation Area, which is located along the outer continental shelf, south of Monterey Canyon, as well as Soquel Canyon State Marine Conservation Area, which contains most of Soquel Canyon (fig. 1–2). Both of these conservation areas were established in 2007 as part of the first phase of California's Marine Life Protection Act Initiative (MPA; California Department of Fish and Wildlife, 2008). Other designated conservation and (or) recreation areas in the onshore part of the map area include Salinas River National Wildlife Refuge, Elkhorn Slough State Marine Conservation Area, Elkhorn Slough State Marine Reserve, Moss Landing Wildlife Area, Zmudowski State Beach, Salinas River State Beach, and Marina Dunes Preserve.

Monterey Bay, a geologically complex area within a tectonically active continental margin (McHugh and others 1998), lies in a zone between two major, converging strike-slip faults. The northwest-striking San Andreas Fault, about 34 km east of Monterey Bay, is the main structure of the Pacific–North American plate boundary. The section of the San Andreas Fault east of the map area ruptured in both the 1989 M6.9 Loma Prieta earthquake and the 1906 M7.8 great California earthquake. The northwest-striking San Gregorio Fault (Dickinson and others, 2005) crosses Monterey Canyon west of Monterey Bay, a few kilometers west of the California State Waters limit (fig. 1–1). Between these two regional faults, strain is accommodated by the diffuse, 10- to 15-km-wide, northwest-striking Monterey Bay Fault Zone (Greene, 1977; Greene and others 1989), which traverses Monterey Bay and cuts through the western part of the Monterey Canyon and Vicinity map area. Deformation associated with these major regional faults and related structures has resulted in uplift of the Santa Cruz Mountains on the north flank of Monterey Bay, as well as uplift of the granitic highlands of the Monterey peninsula on the south flank of Monterey Bay (Anderson, 1990).

Monterey Canyon, which is the main physiographic feature within the map area, begins in the nearshore area in the littoral zone directly offshore of Moss Landing and Elkhorn Slough. The submarine canyon can be traced for more than 400 km seaward, out to water depths of more than 4,000 m on the Monterey Fan, about 265 km southwest of the map area (Paull and others, 2011). Within the map area, the canyon can be traced for about 42 km to a maximum water depth of about 1,520 m at the limit of California State Waters. This canyon system likely is one of the most studied submarine canyons in the world, owing to its depth and complexity, as well as its location adjacent to major marine research facilities. The first indication that the canyon existed was in 1853 when the U.S. Coast and Geodetic Survey recorded depths greater than 120 fathoms (219.5 m) close to shore in the central part of Monterey Bay (Greene and others, 2002); Shepard and Emery (1941) provided the first reconnaissance description. More recent studies using higher resolution multibeam bathymetry data have described the canyon's morphology in great detail (see, for example, Greene and others, 2002; Paull and others, 2005a; Smith and others, 2007; Paull and others, 2011).

The head of Monterey Canyon consists of three branches that begin about 150 m offshore of Moss Landing Harbor. At 500 m offshore, the canyon is already 70 m deep and 750 m wide. The canyon has a V-shaped cross section in the map area (Greene and others, 2002), with walls that generally slope between 10° and 30°. One of the steepest slopes is an almost vertical (80°), 150-m-high face along the south wall across from where Soquel Canyon enters Monterey Canyon. In the map area, Monterey Canyon contains three major meanders, Gooseneck meander, Monterey meander, and San Gregorio meander (fig. 1–2) (Greene and others, 2002); its meandering pattern is similar to that of terrestrial rivers (Paull and others, 2005a). The channel of the axial canyon has a relatively narrow thalweg, which ranges in width from 40 m at its tight bends and restrictions (for example, "Navy Slump;" see fig. 1–2) to as much as 400 to 500 m where Soquel Canyon enters Monterey Canyon and also near the west edge of the map area. Large sand waves, which have heights from 1 to 3 m and wavelengths of about 50 m (Smith and others, 2007; Xu and others, 2008), are present along the channel axis in the upper 4 km of the canyon.

Monterey Canyon crosses the limit of California's State Waters twice, once about 3 km west of its confluence with Soquel Canyon, and again to the south near the San Gregorio meander (see fig. 1–2). Water depth at the San Gregorio meander is about 1,520 m, the deepest point, by far, in all of California's State Waters. For comparison, maximum depths elsewhere in California's State Waters are 820 m in the San Pedro Basin offshore of Los Angeles (about 470 km south of the map area), 570 m in Mugu Canyon offshore of Point Mugu (about 380 km south of the map area), and 560 m in Mendocino Canyon offshore of Cape Mendocino (about 460 km north of the map area).

Soquel Canyon, 9 km long and relatively straight, is the most prominent of the tributary submarine canyons within the map area. The head of Soquel Canyon, about 11 km south of the northern Monterey Bay shoreline, is isolated from coastal watersheds and, thus, is considered inactive as a conduit for coarse sediment transport (Paull and others, 2011). At its confluence with Monterey Canyon (980 m water depth), the mouth of Soquel Canyon is partly blocked by a slump of the canyon walls (Greene and others, 1989) (see also, sheets 4, 10 of this report).

North and south of Monterey and Soquel Canyons, the continental shelf is relatively flat and contains only a few rocky outcrop exposures, most notably on the canyon rims and in the Portuguese Ledge State Marine Conservation Area (fig. 1–2). Bedrock in the inner shelf to midshelf area is covered largely by sediment derived from the Salinas and Pajaro Rivers. This shelf generally is considered to be wave dominated (Storlazzi and Reid, 2010), and the geology and morphology is the product of shoreline migration associated with fluctuating sea level, as well as local tectonics (Eittreim and others, 2002; see also, sheets 8, 10 of this report). North of Monterey Canyon, the broad and flat continental shelf, which extends beyond the California's State Waters limit, dips gently seaward (about 1° to 2°), so that water depths in the northern part of the map area are about 95 m. To the south, the shelf, which extends to the edge of Monterey Canyon, also dips slightly (1° to 2) to water depths of as much as 150 m along the canyon edge.

Storlazzi and Reid (2010) demonstrated that waves and wind generally follow an annual pattern along the central California coast, including Monterey Bay. During the winter months, waves are higher and have longer periods, and they come from a more northerly direction as large winter storms propagate across the North Pacific Ocean. During the summer months, waves generated by more local winds are smaller and have shorter periods. Most coastal sediment transport is associated with the larger winter swells.

The Monterey Canyon and Vicinity map area splits two littoral cells, the Santa Cruz littoral cell (north of Monterey Canyon) and the southern Monterey littoral cell (south of Monterey Canyon) (see fig. 1–2) (Patsch and Griggs, 2007). Sand generally travels east and south in the Santa Cruz littoral cell; sand is supplied through sea cliff erosion, as well as from the San Lorenzo River, the Pajaro River, and several other smaller coastal watersheds. In addition, about 200,000 yd^3/yr (about 152,911 m^3/yr) of sand is dredged from the entrance channel to the Santa Cruz Small Craft Harbor (about 13 km north of the map area; see fig. 1–1) and then placed on beaches to the east (downdrift) of it (Patsch and Griggs, 2007). This sand feeds the beaches in the southeastern reach of the littoral cell and (or) is eventually trapped and lost by Monterey Canyon.

The Monterey Canyon and Vicinity map area also includes two of the three subcells of the southern Monterey Bay littoral cell (Patsch and Griggs, 2007). From the head of Monterey Canyon to the Salinas River, littoral drift is dominantly to the north (subcell SMB_1 in fig. 1–2). Sand entering the ocean from the Salinas River either is deposited offshore in a large subaqueous delta (see sheet 9) or travels north in the littoral zone, nourishing the beaches until it is transported down Monterey Canyon. Dams along the Salinas River have reduced its original sand yield by 33 percent (Willis and Griggs, 2003). From south of the Salinas River to the southern extent of the map area, coastal sediment is moved mainly to the south (subcell SMB_2 in fig. 1–2). Dune erosion is the only significant source of sand in this subcell (Patsch and Griggs, 2007). It is estimated that about 400,000 m^3/yr of sand on average enters Monterey Canyon from both the Santa Cruz and southern Monterey littoral cells (Paull and others, 2005a; Patsch and Griggs, 2007).

Publication Summary

This publication about the Monterey Canyon and Vicinity 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 five different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data mainly highlight Monterey Canyon, the deepest and most complex submarine canyon within California’s State Waters. 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 “potential habitats,” which are delineated on the basis of substrate type, geomorphology, seafloor process, or other attributes that may provide a habitat for a specific species or assemblage of organisms. Sheet 8 compiles representative seismic-reflection profiles from the map area, providing information on the subsurface stratigraphy and structure of the map area. Sheet 9 shows the distribution and thickness of young sediment (deposited over the last about 21,000 years, during the most recent sea-level rise) in both the map area and the larger 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 the integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

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

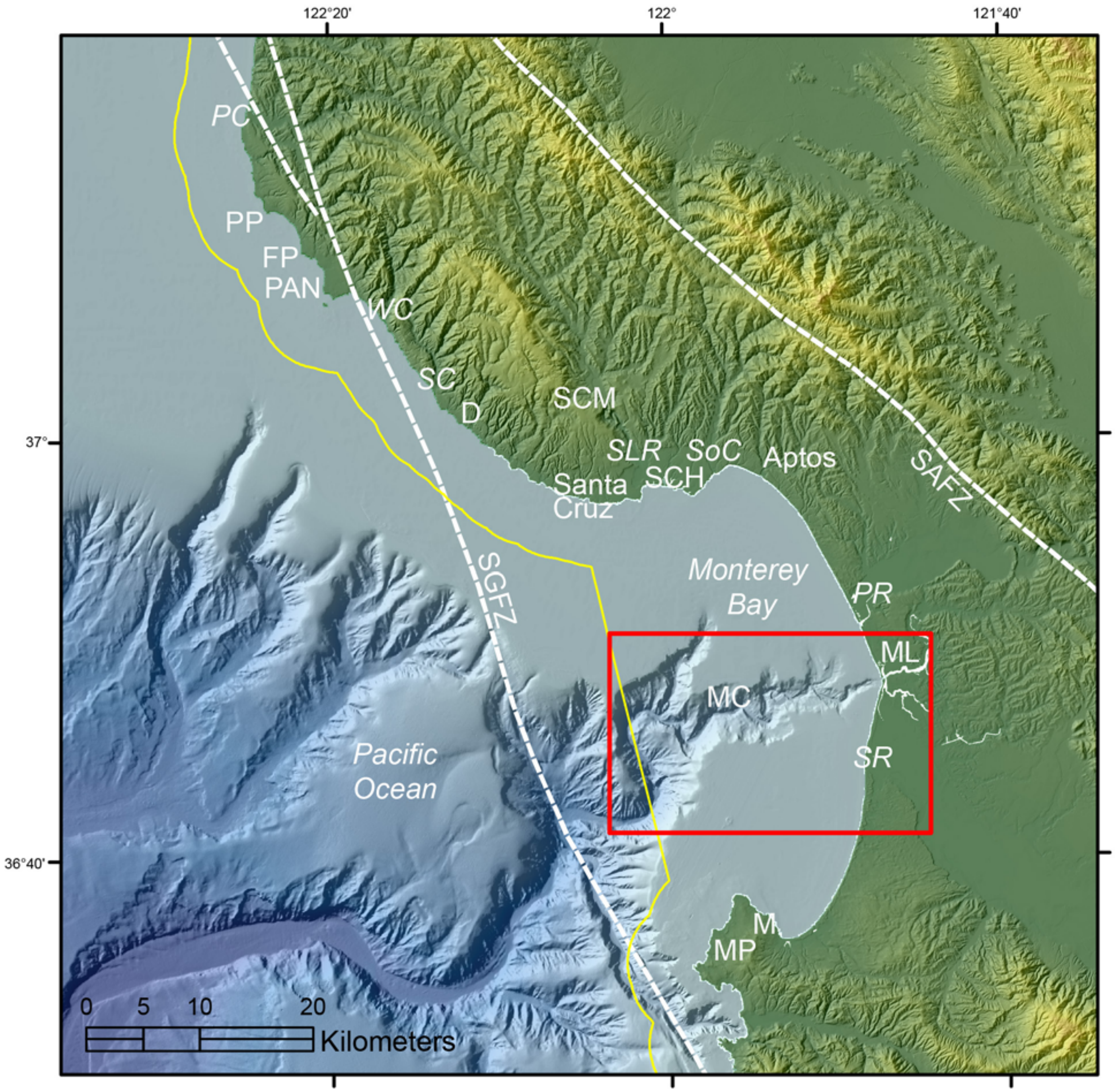

Figure 1–1. Physiography of Pigeon Point to southern Monterey Bay region and its environs. Box shows Monterey Canyon and Vicinity map area. Yellow line shows limit of California's State Waters. Dashed white lines show traces of San Gregorio Fault Zone (SGFZ) and San Andreas Fault Zone (SAFZ). Other abbreviations: D, Davenport; FP, Franklin Point; M, Monterey; MC, Monterey Canyon; ML, Moss Landing; MP, Monterey peninsula; PAN, Point Año Nuevo; PC, Pescadero Creek; PP, Pigeon Point; PR, Pajaro River; SC, Scott Creek; SCH, Santa Cruz Small Craft Harbor; SCM, Santa Cruz Mountains; SLR, San Lorenzo River; SoC, Soquel Creek; SR, Salinas River; WC, Waddell Creek.

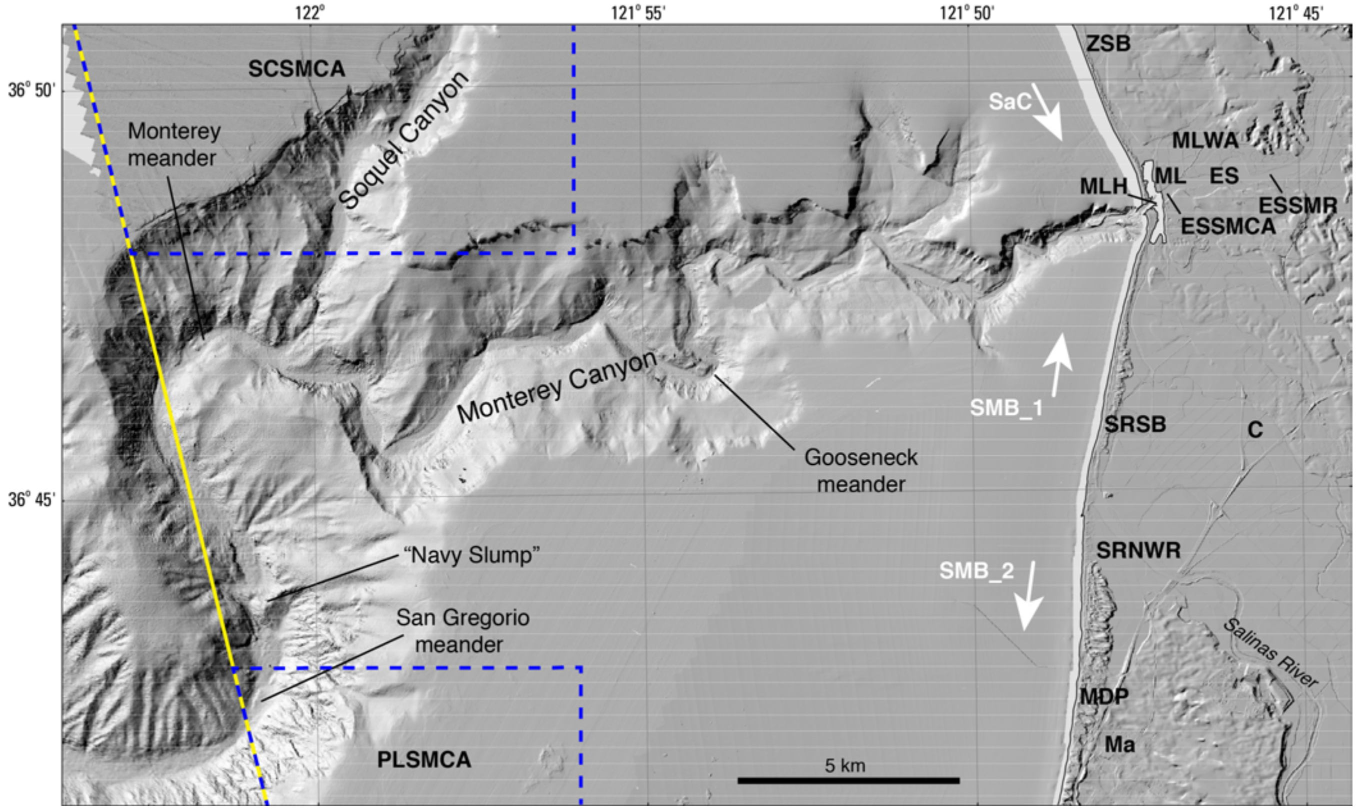

Figure 1–2. Coastal and offshore geography of Monterey Canyon and Vicinity map area. Yellow line shows limit of California's State Waters. Dashed blue lines show boundaries of Portuguese Ledge State Marine Conservation Area (PLSMCA) and Soquel Canyon State Marine Conservation Area (SCSMCA); note that entire offshore part of map area is contained within Monterey Bay National Marine Sanctuary. White arrows show general flow directions of local littoral cells: SaC, Santa Cruz littoral cell; SMB_1, SMB_2, two (of three) subcells of southern Monterey littoral cell. Other abbreviations: C, Castroville; ES, Elkhorn Slough; ESSMCA, Elkhorn Slough State Marine Conservation Area; ESSMR, Elkhorn Slough State Marine Reserve; Ma, Marina; MDP, Marina Dunes Preserve; ML, Moss Landing; MLH, Moss Landing Harbor; MLWA, Moss Landing Wildlife Area; SRNWR, Salinas River National Wildlife Refuge; SRSB, Salinas River State Beach; ZSB, Zmudowski State Beach.

Chapter 2. Bathymetry and Backscatter-Intensity Maps for the Monterey Canyon and Vicinity 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 Monterey Canyon and Vicinity map area in central California were generated from bathymetry and backscatter data collected by the Monterey Bay Aquarium Research Institute (MBARI), California State University, Monterey Bay (CSUMB), and the U.S. Geological Survey (USGS) (fig. 1 on sheets 1, 2, 3). Mapping was completed between 1998 and 2014, using a combination of 30-kHz Simrad EM-300 and 200-kHz/400-kHz Reson 7125 multibeam echosounders, as well as 234-kHz and 468-kHz SEA SWATHplus phase-differencing sidescan sonars. These mapping missions combined to collect both bathymetry (sheets 1, 2) and acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 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 MBARI mapping mission in 1998, an Applied Analytic POS MV (Position and Orientation System for Marine Vessels) was used to accurately position the vessel during data collection, and it also accounted for vessel motion with navigational input from a kinematic differential global positioning system (DGPS) system. Soundings were corrected for variations in water-column sound velocity using data from SeaBird CTD (conductivity, temperature, and depth) and Sippican T5 expendable bathythermographs. The USGS downloaded the original MBARI survey line files from the National Centers for Environmental Information 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.

During the CSUMB mapping missions in 2008 and 2009, an Applanix POS MV was used to accurately position the vessels during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm), with input from a NavCom 2050 GPS receiver (CNAV). Kinetic GPS (KGPS) altitude data were used to account for tide-cycle fluctuations, and sound-velocity profiles were collected with an Applied Microsystems SVPlus sound velocimeter. Soundings were corrected for vessel motion using the Applanix POS MV data, for variations in water-column sound velocity using the AM SVPlus data, and for variations in water height (tides) using vertical-position data from the GPS receivers. Multibeam backscatter data were processed using Geocoder. Within Geocoder, the backscatter intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. After the lines were corrected, they were mosaicked into 1- 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 geographic information system (GIS), and converted to GRIDs at 2-m resolution.

During the USGS mapping missions in 2009 and 2014, GPS data with real-time-kinematic corrections were combined with measurements of vessel motion (heave, pitch, and roll) in a CodaOctopus F180 attitude-and-position system (2009) and an Applanix POS MV (2014) to produce a high-precision vessel-attitude packet. This packet was transmitted to the acquisition software in real time and combined with instantaneous sound-velocity measurements at the transducer head before each ping. The returned samples were projected to the seafloor using a ray-tracing algorithm that works with previously measured sound-velocity profiles. Statistical filters were applied to discriminate seafloor returns (soundings) from unintended targets in the water column (Ritchie and others, 2010). Further sounding cleaning was completed in Caris HIPS and SIPS software. Finally, the soundings were converted into 2-m-resolution bathymetric-surface-model grids.

The backscatter data collected by CSUMB and USGS were postprocessed using USGS software (D.P. Finlayson, 2011, written commun.) 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.

Processed soundings from the different mapping missions were exported from the acquisition or processing software as XYZ files and bathymetric-surface models. Individual bathymetric-surface models that had similar spatial resolutions were then merged together and clipped to the boundary of the map area. The shallower USGS and CSUMB bathymetric-surface model has a spatial resolution of 2 m, whereas the deeper MBARI surface model has a 5-m resolution. 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 straight lines that are apparent within the map area are data-collection and -processing artifacts. These 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 original surfaces were smoothed using the Focal Mean tool in ArcGIS and a circular neighborhood that has a radius of between 20 and 30 m (depending on the area). The contours were generated from these smoothed surfaces using the Spatial Analyst Contour tool in ArcGIS. The most continuous contour segments were preserved; smaller segments and isolated island polygons were excluded from the final output. 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. The shallower USGS and CSUMB acoustic backscatter grids have a spatial resolution of 2 m, whereas the deeper MBARI grid has a 5-m resolution. 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. Data gaps in the deeper section of Monterey Canyon (in the southwest corner of the map area) are where backscatter soundings are less dense, which results in no data being found within a 5-m grid cell.

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 (NOAA) 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 Monterey Canyon and Vicinity 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 Monterey Canyon and Vicinity 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 Monterey Canyon and Vicinity map area (sheet 4).

The maps and three-dimensional views on sheet 4 were created using a series of geographic information systems (GIS) and visualization techniques. Using GIS, the bathymetric and topographic data (sheet 1) were converted to ASCIIRASTER format files, and the acoustic-backscatter data (sheet 3) were converted to geoTIFF images. The bathymetric and topographic data were imported in the Fledermaus® software (QPS). The bathymetry was color-coded to closely match the colored shaded-relief bathymetry on sheet 1, in which reds represent shallower depths and purples represent deeper depths. Acoustic-backscatter geoTIFF images also were draped over the bathymetry data. Topographic data were shown in gray shades. The colored bathymetry, topography, and draped backscatter were then tilted and panned to create the perspective views such as those shown in figures 1, 2, 3, 5, 6, and 7 on sheet 4. These figures mainly highlight Monterey Canyon, the deepest and most complex submarine canyon within California's State Waters.

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

Block diagrams that combine the bathymetry with seismic-reflection profile data help integrate surface and subsurface observations, especially stratigraphic and structural relations (for example, fig. 7, on sheet 4). These block diagrams were created by converting digital seismic-reflection-profile data (see sheet 8) into TIFF images, while taking note of the starting and ending coordinates and maximum and minimum depths. The images were then imported into the Fledermaus® software as vertical images and merged with the bathymetry imagery.

Chapter 4. Seafloor-Character Map of the Monterey Canyon and Vicinity 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 five substrate classes are identified in the Monterey Canyon and Vicinity map area:

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

The seafloor-character map of the Monterey Canyon and Vicinity 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. 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). Class V (hard anthropogenic material) values were determined on the basis of their visual characteristics and the known location of man-made features. The resulting map (gridded at 2 m) was cleaned by hand to remove data-collection artifacts (for example, the trackline nadir).

On the seafloor-character map (sheet 5), the five 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 Monterey Canyon and Vicinity 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 Monterey Canyon and Vicinity map area, Slope Classes 1, 2, and 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.

Fine- to medium-grained smooth sediment (sand and mud) makes up 77.1 percent (312.2 km^2) of the map area: 8.9 percent (36.0 km^2) is in Depth Zone 2, 37.2 percent (150.6 km^2) is in Depth Zone 3, 11.1 percent (44.9 km^2) is in Depth Zone 4, and 19.9 percent (80.7 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 16.0 percent (64.8 km^2) of the map area: 0.1 percent (0.3 km^2) is in Depth Zone 2, 2.5 percent (10.1 km^2) is in Depth Zone 3, 2.5 percent (10.3 km^2) is in Depth Zone 4, and 10.9 percent (44.1 km^2) is in Depth Zone 5. Rock and boulder, rugose (rock and boulder outcrops having high surficial complexity) makes up 6.5 percent (26.4 km^2) of the map area: less than 0.1 percent (<0.1 km^2) is in Depth Zone 2, 0.1 percent (0.6 km^2) is in Depth Zone 3, 0.4 percent (1.6 km^2) is in Depth Zone 4, and 6.0 percent (24.2 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 0.3 percent (1.3 km^2) of the map area: 0.2 percent (0.9 km^2) is in Depth Zone 2, 0.1 percent (0.3 km^2) is in Depth Zone 3, and less than 0.1 percent (0.1 km^2) is in Depth Zone 4. Anthropogenic material (a pipe) makes up less than 0.1 percent (<0.1 km^2) of the map area: less than 0.1 percent (<0.1 km^2) is present in both Depth Zone 2 and 3. The seafloor-character classification also is summarized on sheet 5 in table 1.

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.” Class V values are determined from the visual characteristics and known location of man-made features.

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

The continental shelf in the Monterey Canyon and Vicinity map area is mainly flat with local, small sedimentary-bedrock exposures (Class III). The seabed is predominantly covered by Class I sediment composed of soft, unconsolidated sand and mud. A few rugose rock outcrops (Class III) are exposed on the continental shelf, situated mostly along the shelf-canyon interface. Exposed rock is covered intermittently by varying thicknesses of fine- (Class I) to coarse-grained (Class II) sediment (coarse sand and gravel). A few large scour depressions (Class IV) are dispersed in the shallow nearshore area (intertidal to 50 m), just north of Moss Landing near the head of the canyon. One anthropogenic feature, an outfall pipeline, is present near the south edge of the map area. The large Monterey Canyon, which dominates the rest of the map area, is characterized by steeper slopes (down to 1,747 m water depth), abundant mixed sediment (Class II), and some hard rock exposures (Class III) along the canyon walls.

The classification accuracy of Class I (2-m-resolution grid, 84 percent accurate; 5-m-resolution grid, 85 percent accurate; table 4–2) is determined by comparing the shipboard video observations and the classified map. Class IV also showed a high accuracy value within the 2-m-resolution grid (94 percent accurate); no video observations of Class IV sediments were retrieved over the 5-m-resolution grid, and, therefore, no accuracy assessments were performed. The weaker agreements in Class II (2-m-resolution grid, 51 percent accurate; 5-m-resolution grid, 49 percent accurate) and Class III (2-m-resolution grid, 35 percent accurate; 5-m-resolution grid, 42 percent accurate) likely are due to (1) the distribution of small, localized rock outcrops, (2) the relatively narrow and intermittent nature of transition zones from sediment to rock, and (3) the size of the buffer. The bedrock outcrops in this area are composed of differentially eroded sedimentary rocks (Cochrane and Lafferty, 2002). Erosion of softer layers produces Class I and II sediments, resulting in patchy areas of rugose rock and boulder

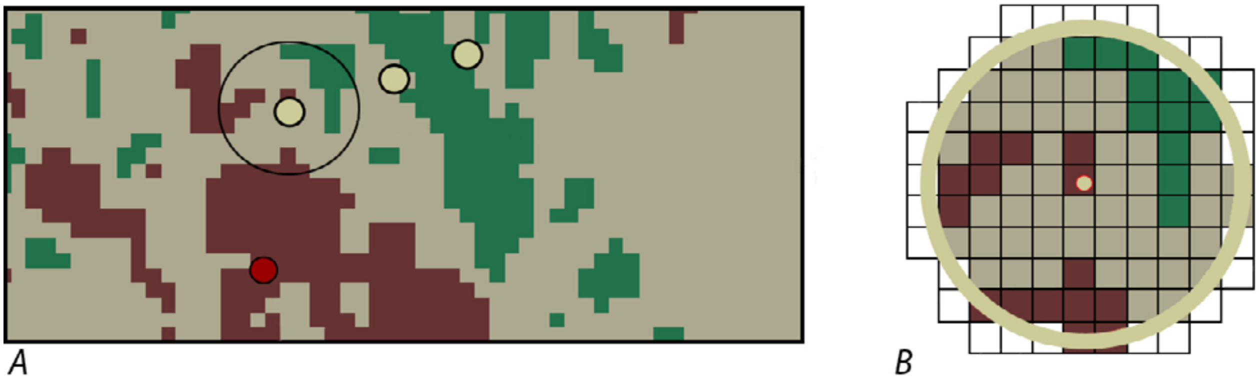

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

habitat (Class III) 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.

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 (98 percent for Class I, 99 percent for Class II, 77 percent for Class III, and 100 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 all classes that have video observations (95 percent for Class I, 87 percent for Class II, and 73 percent for Class III). No video observations or sediment samples were retrieved of Class IV (scour depressions) substrate over the 5-m-resolution grid and Class V (hard anthropogenic feature, pipe) substrate of either (2- or 5-m) resolution; therefore, no accuracy assessments were performed for these classes.

Table 4–1. Conversion table showing how video observations of primary substrate (more than 50 percent seafloor coverage), secondary substrate (more than 20 percent seafloor coverage), and abiotic seafloor complexity (in first three columns) are grouped into seafloor-character-map Classes I, II, and III for use in supervised classification and accuracy assessment in Monterey Canyon and Vicinity 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	mud	moderate	
mud	sand	low	
sand	mud	low	
sand	mud	moderate	
sand	sand	low	
sand	sand	moderate	
			sediment
			ripples
Class II			
boulders	cobbles	moderate	
boulders	mud	moderate	
cobbles	gravel	moderate	
cobbles	mud	low	
cobbles	rock	low	
cobbles	rock	moderate	
cobbles	sand	moderate	
gravel	mud	low	
gravel	rock	low	
mud	cobbles	low	
mud	gravel	low	
mud	rock	low	
mud	rock	moderate	
rock	gravel	low	
rock	mud	low	
rock	sand	low	
rock	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 Monterey Canyon and Vicinity map area.—Continued

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

Table 4–2. Accuracy-assessment statistics for seafloor-character-map classifications in Monterey Canyon and Vicinity map area.

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

Class	Number of observations	% majority	% presence/absence
2-m-resolution grid			
I—Fine- to medium-grained smooth sediment	354	83.7	97.7
II—Mixed smooth sediment and rock	65	50.9	98.5
III—Rock and boulder, rugose	17	34.6	76.5
IV—Medium- to coarse-grained sediment (in scour depressions)	44	93.9	100.0
V—Hard anthropogenic feature	0	N/A	N/A
5-m-resolution grid			
I—Fine- to medium-grained smooth sediment	466	84.5	94.6
II—Mixed smooth sediment and rock	126	49.3	86.5
III—Rock and boulder, rugose	63	42.4	73.0
IV—Medium- to coarse-grained sediment (in scour depressions)	0	N/A	N/A
V—Hard anthropogenic feature	0	N/A	N/A

Chapter 5. Ground-Truth Studies for Monterey Canyon and Vicinity 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 Monterey Canyon and Vicinity 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 137 trackline kilometers of video and more than 25,000 still photographs, in addition to 1,369 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

During the ground-truth surveys, 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.

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

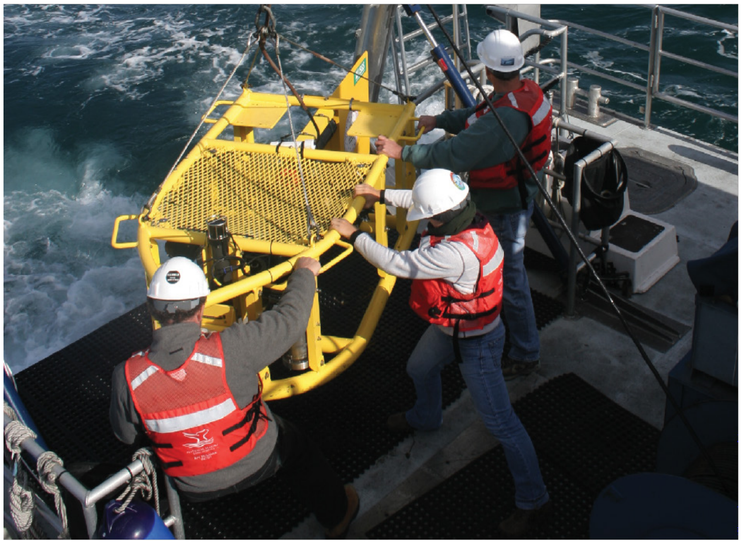

Figure 5–1. Photograph of camera sled being prepared to be launched off ship for ground-truth survey.

(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 E); 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 Monterey Canyon and Vicinity map area is dominated by mud and sand, with lesser amounts of rock (see also, sheets 5, 7, 10).

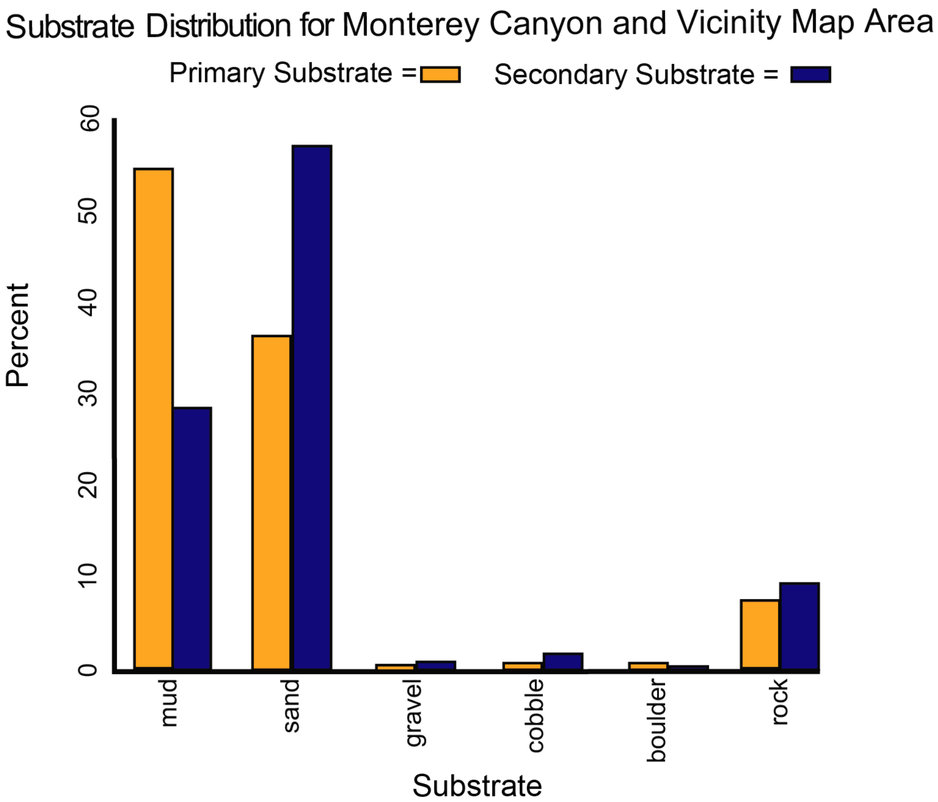

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Monterey Canyon and Vicinity map area.

Chapter 6. Potential Marine Benthic Habitats of the Monterey Canyon and Vicinity Map Area (Sheet 7)

By H. Gary Greene and Charles A. Endris

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

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

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

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

Classifying Potential Marine Benthic Habitats

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

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

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

E = Estuary (0 to 100 m)
S = Shelf; continental and island shelves (0 to 200 m)
F = Flank; continent slope (200 to 3,000 m)

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

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

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

b = Beach, relict (submerged) or shoreline
(b)/p = Pinnacle indistinguishable from boulder
c = Canyon
c(b) = Bar within thalweg
c(c) = Curve or meander within thalweg
c(f) = Fall or chute within thalweg
c(h) = Canyon head
c(m) = Canyon mouth
c(t) = Thalweg
c(w) = Canyon wall
d = Deformed, tilted, and (or) folded bedrock; overhang
e = Exposure; bedrock
g = Gully; channel
h = Hole; depression
l = Landslide
m = Mound; linear ridge
p = Pinnacle; cone
s = Scarp, cliff, fault, or slump scar
t = Terrace

w = Dynamic bedform

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

_a = Anthropogenic (artificial reef, breakwall, shipwreck, disturbance)
_a-dd = Dredge disturbance
_a-dg = Dredge groove or channel
_a-dm = Dredge mound (disposal)
_a-dp = Dredge pothole
_a-f = Ferry (or other vessel) propeller-wash scour or scar
_a-g = Groin, jetty, rip-rap
_a-p = Pipeline
_a-td = Trawl disturbance
_b = Bimodal (conglomeratic, mixed [gravel, cobbles, and pebbles])
_c = Consolidated sediment (claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
_d = Differentially eroded
_f = Fracture, joint; faulted
_g = Granite
_h = Hummocky, irregular relief
_r = Ripple (amplitude, greater than 10 cm)
_s = Scour (current or ice; direction noted)
_u = Unconsolidated sediment

Seafloor Slope—Denotes slope, typically calculated from XYZ high-resolution bathymetry data. Depicted on map by number, listed after modifier:

1 = Flat (0°–5°)
2 = Sloping (5°–30°)
3 = Steeply sloping (30°–45°)
4 = Vertical or near vertical (45°–90°)
5 = Overhanging (more than 90°)
6 = Unknown

Examples of Attribute Coding

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

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

Map Area Habitats

The Monterey Canyon and Vicinity map area includes the nearshore and inner continental shelf areas directly west of Moss Landing, Elkhorn Slough, and the mouth of the Salinas River, and it also includes part of the Monterey Canyon system (including Soquel Canyon). Delineated on the map are 49 potential marine benthic habitat types: 44 types are located on the continental shelf (“Shelf” megahabitat), and 5 are located on the continental slope (“Flank” megahabitat) within the submarine canyons. The meso- and macrohabitats on the continental shelf include soft, unconsolidated sediment (23 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 (10 habitat types) such as soft sand and gravels that overlie hard consolidated sedimentary bedrock or granitic basement rocks; hard substrate (8 habitat types) such as deformed and differentially eroded bedrock, granitic outcrops, pinnacles, and boulders; and anthropogenic features (3 habitat types) such as riprap and a jetty, a pipeline, and a dredged channel.

Acoustic-backscatter data show that most of the area is underlain by "soft" materials, consistent with the interpretation that unconsolidated sediments dominate the seafloor in the map area. Sedimentary processes are quite active, especially on the inner shelf near the head of Monterey Canyon, and, thus, habitats are highly dynamic. Coastal sediment transport is primarily to the south-southeast on the north side of Monterey canyon; south of the canyon, transport is primarily to the north. Bedrock exposures are found on the canyon's rim, walls, and thalwegs, as well as in local isolated areas on the continental shelf. These rocky exposures potentially provide good habitat for rockfish (*Sebastes* spp.), as well as sessile organisms and other attached invertebrates. Additionally, the submarine canyons provide a conduit for the upwelling of deep, nutrient-rich waters that support an abundant variety of marine life, including pelagic fishes and marine mammals. The Monterey Canyon system is well known as a significant biological "hot spot" for marine life.

Of the total of 410 km^2 mapped in the Monterey Canyon and Vicinity map area, 385.64 km^2 (94.1 percent) is mapped on the continental shelf, and 24.36 km^2 (5.9 percent) is mapped on the flank or continental slope. On the continental shelf, soft, unconsolidated sediment is the dominant habitat type, covering 242.36 km^2 (59.1 percent). Mixed hard-soft substrate covers 109.63 km^2 (26.7 percent), and hard rock covers 33.52 km^2 (8.2 percent). Anthropogenic substrate covers only 0.13 km^2 (0.03 percent) and, thus, is not significant. On the continental slope, mixed hard-soft substrate is the dominant habitat type, covering 21.43 km^2 (5.2 percent). Soft, unconsolidated sediment covers 1.76 km^2 (0.4 percent), and hard rock covers 1.17 km^2 (0.3 percent).

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

By Katherine L. Maier, Samuel Y. Johnson, Stephen R. Hartwell, and Ray W. Sliter

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 Monterey Canyon and Vicinity map area. These data, which are collected at several resolutions, extend to varying depths in the subsurface, depending on the purpose and mode of data acquisition. The seismic-reflection profiles (sheet 8) provide information on sediment character, distribution, and thickness, as well as potential geologic hazards, including active faults, areas prone to strong ground motion, and tsunamigenic slope failures. The information on faults provides essential input to national and state earthquake-hazard maps and assessments (for example, Petersen and others, 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 uppermost sediment unit; the depth to base of this uppermost unit; and both the local and regional distribution of faults and earthquake epicenters (data from U.S. Geological Survey and California Geological Survey, 2010; Northern California Earthquake Data Center, 2014).

Data Acquisition

Most seismic-reflection profiles displayed on sheet 8 (figs. 1, 2, 3, 4, 5, 7, 8, 10, 11) were collected in 2009 and 2011 on U.S. Geological Survey (USGS) cruises S–N1–09–MB and S–6–11–MB, respectively (Sliter and others, 2013), using the SIG 2Mille minisparker system. This system used a 500-J high-voltage electrical discharge fired 1 to 4 times per second, which, at normal survey speeds of 4 to 4.5 nautical miles/hour, gives a data trace every 0.5 to 2.0 m of lateral distance covered. The data were digitally recorded in standard SEG-Y 32-bit floating-point format, using Triton Subbottom Logger (SBL) software that merges seismic-reflection data with differential GPS-navigation data. After the survey, a short-window (20 ms) automatic gain control algorithm was applied to the data, along with a 160- to 1,200-Hz bandpass filter and a heave correction that uses an automatic seafloor-detection window (averaged over 30 m of lateral distance covered). 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.

Figures 6 and 9 on sheet 8 show migrated, deep-penetration, multichannel seismic-reflection profiles collected in 1976 and 1982 by WesternGeco on cruises W–14–76–SF and W–34–82–MB, respectively. These profiles 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 from four different surveys in the Monterey Canyon and Vicinity map area, providing imagery of the subsurface geology. The continental shelf in the map area is incised by Monterey Canyon and its tributaries, including Soquel Canyon. Outside of Monterey Canyon, the relatively flat (<1.0°) shelf extends from the shoreline to water depths of about 100 to 120 m. This shelf is underlain by Cretaceous granitic basement rocks, Neogene sedimentary rocks, Pleistocene paleochannel and canyon-fill deposits, and uppermost Pleistocene to Holocene sediments. Granitic basement rocks are characterized as massive, reflection-free zones on deeper penetration industry seismic-reflection profiles (see, for example, figs. 6, 9 on sheet 8). Neogene sedimentary rocks, which predominantly consist of the late Miocene and Pliocene Purisima Formation, are characterized on high-resolution and multichannel seismic-reflection profiles (see, for example, figs. 1, 5, 6, 7, 8, 9 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.

Seismic-reflection profiles near the head of Monterey Canyon and at the mouths of the Salinas River (south of Monterey Canyon) and the Pajaro River (north of Monterey Canyon, about 700 m north of the map area) reveal nested, sediment-filled channel complexes (see, for example, figs. 2, 3, 4, 5 on sheet 8). Erosional relief can be 200 m or more, and the depth of erosion can exceed 300 m below sea level; in addition, channel-fill deposits include numerous undulatory, internal-erosion surfaces. Reflections within the Pleistocene paleochannel and canyon-fill deposits typically are parallel to subparallel, low amplitude, high frequency, and moderately continuous. The evolution of these channel complexes and the head of Monterey Canyon is linked to the Quaternary history of sea-level fluctuations (see, for example, Waelbroeck and others, 2002) and the channel-fill deposits are interpreted to include a complex stacking of fluvial, eolian, and marine deposits. Most channels are presumed to have been cut during sea-level lowstands (sea level as much as 130 m below present-day levels) by erosive, sediment-rich flows emanating from the migrating mouths of the Salinas and Pajaro Rivers. Depth of channel incision (>300 m), channel location, and channel morphology indicate that much of the erosion must have occurred below sea level, in a submarine-canyon environment. Conversely, most of the channel fill is inferred to have been deposited during sea-level highstands when river mouths may not have been directly connected to the head of the paleochannel and (or) canyon. The Pleistocene paleochannel and canyon-fill deposits are found along about 12 kilometers of the coast, indicating that the morphology of the head of Monterey Canyon varied significantly during the Pleistocene, possibly having been much broader than present-day and (or) having shifted location numerous times. These channel complexes have lower slope stability than that of the underlying bedrock, and their location along the canyon rim could be an important control on slope stability and the presence of intracanyon landslides (see figs. 2, 5, 9, 10 on sheet 8).

Eustasy also was an important control on latest Pleistocene to Holocene shelf deposition in the Monterey Canyon and Vicinity 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 125 m lower during the LGM, at which time the shelf surrounding Monterey Canyon 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 the high-resolution seismic-reflection profiles (figs. 1, 2, 3, 4, 5, 7, 8, 10, 11 on sheet 8), and their thicknesses are shown on sheet 9.

Post-LGM shelf sediments, which unconformably overlie both bedrock and the Pleistocene paleochannel and canyon-fill deposits in the Monterey Canyon and Vicinity map area, are characterized by subparallel, low- to moderate-amplitude, locally diffuse, laterally continuous 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). The thickest sediments are found in a prominent, shore-parallel, elongate (about

4 km long and 2 km wide) bar, located offshore of the mouth of the Salinas River (figs. 8, 10, 11 on sheet 8). The geometry of reflections within the mound indicates both vertical aggradation and low-angle, seaward progradation.

Seismic-Reflection Imaging of Monterey Canyon and Soquel Canyon

Monterey Canyon and its tributaries, including Soquel Canyon, incise bedrock and sediments through the continental shelf in the Monterey Canyon and Vicinity map area, creating as much as several hundreds of meters of relief on the seafloor. Only a few high-resolution seismic-reflection profiles intersect the canyon system, and few of the high-resolution profiles cross Monterey Canyon. Where high-resolution seismic-reflection profiles are available in Monterey Canyon, the quality and resolution is less than that of adjacent seismic-reflection data on the shelf. Side-echoes and diffractions are abundant, and they obscure subsurface reflectivity in the canyons, especially in the canyon walls. A few deep-penetration, multichannel seismic-reflection profiles cross Monterey Canyon (figs. 6, 9 on sheet 8); however, these profiles image reflections at larger scales and lower resolutions than that of the high-resolution seismic-reflection profiles.

Major geologic and geomorphic features within Monterey and Soquel Canyons that are imaged in seismic-reflection profiles include steep canyon walls, bedrock outcrops, landslides, and axial channels. The proximal Monterey Canyon walls primarily are covered by muddy Quaternary sediments (Paull and others, 2005a, 2010), imaged where they are thick as continuous to semicontinuous, parallel to subparallel reflections (fig. 5 on sheet 8). Canyon walls contain small areas of decreased slope that accumulate muddy sediments (Paull and others, 2005a, 2010), potentially including marine, hemipelagic, turbiditic, and landslide deposits. These areas, which are termed “benches” (terminology from Paull and others, 2010; Maier and others, 2012), are imaged in seismic-reflection profiles as relatively flat sections that are draped by moderate-amplitude, continuous, parallel to subparallel reflections (fig. 5 on sheet 8). Canyon walls contain both landslide scarps, which are imaged in seismic-reflection profiles as truncated reflections below the seafloor, and landslide deposits, which are imaged as mounded deposits that have chaotic to continuous, low- to moderate-amplitude reflections (see figs. 2, 5, 9, 10 on sheet 8).

Canyon walls in the distal (within the map area) part of the canyon also contain bedrock outcrops. Granitic bedrock is imaged as massive, reflection-free zones below continuous, parallel to subparallel, variable amplitude, high-frequency reflections that image Neogene sedimentary bedrock (figs. 6, 9 on sheet 8). The Neogene sedimentary bedrock primarily includes the upper Miocene and Pliocene Purisima Formation and the Miocene Monterey Formation; however, these two formations are difficult to distinguish in seismic-reflection profiles (fig. 9 on sheet 8). Surface morphologies (sheets 1, 2), acoustic backscatter (sheet 3), seafloor-sediment and rock samples (Stakes and others, 1999; Paull and others, 2005a,b, 2010), and previously published descriptions (see, for example, Greene, 1977; Barry and others, 1996; Wagner and others, 2002), all are used to help distinguish the Cretaceous granitic rocks of Monterey, the Purisima Formation, and the Monterey Formation, in addition to other bedrock outcrops and sediments, within the Monterey and Soquel Canyon walls.

Both the Monterey and Soquel Canyons contain curvilinear to sinuous axial channels (Paull and others, 2010) that generally are about 100 to 500 m wide (although the Monterey Canyon channel widens downslope), which mark the deepest paths down the canyons. In deep-penetration, multichannel seismic-reflection profiles, the Monterey Canyon axial channel incises into high-amplitude, continuous to semicontinuous, parallel to subparallel reflections that are interpreted to be older canyon sediments and bedrock (figs. 6, 9 on sheet 8). The high-resolution seismic-reflection profiles image moderate- to high-amplitude, discontinuous to chaotic reflections below the axial channel (figs. 5, 10 on sheet 8). The axial channel, which contains coarse-grained (sand and gravel) deposits from frequent downcanyon-flow events, displays minimal reflectivity in higher resolution seismic-reflection profiles (Paull and others, 2005a, 2010; Smith and others, 2005).

Geologic Structure and Recent Deformation

In the Monterey Canyon and Vicinity map area, the shelf north and south of Monterey Canyon 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 (sheet 8) on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as reflection presence, amplitude, frequency, geometry, continuity, and vertical sequence. Seismic-reflection profiles that traverse this diffuse zone cross as many as nine faults over a width of about 8 km (see, for example, fig. 7 on sheet 8). The 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 locally appear to minimally disrupt 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.

Mapping fault strands in the Monterey Bay Fault Zone across the Monterey Canyon system is problematic. The combination of steep relief, increased water depths, and massive to poorly stratified sediment fill generally results in poor quality of both high-resolution and deeper seismic-reflection profiles (see, for example, figs. 2, 3, 4, 5, 6, 7, 9, 10 on sheet 8). High-resolution bathymetry does not reveal obvious tectonic landforms (such as fault lineaments or scarps), likely owing to (1) deformation being distributed across a broad zone, (2) minimal late Quaternary deformation, and (3) active canyon processes. It is important to realize that the Monterey Bay Fault Zone almost certainly crosses the Monterey Canyon system, showing a fault pattern that is similar to what is seen on the continental shelf north and south of the canyon; however, this is not shown on the geologic map (sheet 10) or on structure maps (Maps A, B, E on sheet 9) because conclusive evidence for the locations of individual fault strands within the submarine-canyon system is lacking.

On a regional scale, the Monterey Bay and Vicinity map area lies within a northward-narrowing zone between the San Andreas Fault Zone (about 34 km east of the map area) and the San Gregorio Fault Zone (about 5 km west of the map area), two major structures in the right-lateral transform plate boundary between the North American and Pacific plates. Deformation associated with the Monterey Bay Fault Zone and other structures in the map area accommodates strain that results from this dynamic tectonic setting (Greene, 1990; Dickinson and others, 2005).

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) and from the U.S. Geological Survey’s Quaternary fault and fold database (U.S. Geological Survey and California Geological Survey, 2010). Earthquake epicenters are from the Northern California Earthquake Data Center (2014), which is maintained by the U.S. Geological Survey and the University of California, Berkeley, Seismological Laboratory; all events of magnitude 2.0 and greater for the time period 1967 through 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), the epicenter of which is located 21 km north of the map area, is the most significant event in the region. The largest recorded earthquake in the Monterey Canyon and Vicinity map area (M4.7, 8/4/1970) occurred within the Monterey Bay Fault Zone.

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 Monterey Canyon and Vicinity 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 Soquel 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.

High-resolution seismic-reflection profiles (sheet 8) image (1) a lower unit consisting of deformed Neogene bedrock, (2) a younger unit consisting of Pleistocene paleochannel and canyon-fill deposits that incises the Neogene bedrock, and (3) an upper unit consisting of inferred upper Quaternary marine sediments (shown by blue shading on seismic-reflection profiles in fig. 1 on sheet 9 and in figs. 2, 3, 4, 5, 7, 8, 10, and 11 on sheet 8). This uppermost stratigraphic unit commonly is characterized by low- to moderate-amplitude, low- to high-frequency, parallel to subparallel, continuous to moderately continuous reflections (terminology from Mitchum and others, 1977). The contact between this upper stratigraphic unit and underlying strata is a prominent, locally angular unconformity, commonly marked by minor channeling and an upward change to lower amplitude, more diffuse reflections. This unconformity is an inferred transgressive surface of erosion, and the upper stratigraphic unit is inferred to have been deposited during the post-LGM sea-level rise of about the last 21,000 years (see, for example, Stanford and others, 2011).

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, resulting in thicknesses of as much as about 32 m. The thickness points were interpolated to a preliminary continuous surface, overlaid with zero-thickness bedrock outcrops (see sheet 10), and contoured, following the methodology of Wong and others (2012).

Several factors required manual editing of the preliminary sediment-thickness maps to make the final product. The thickness data points are dense along tracklines (about 1 m apart) and sparse between tracklines (1,000 to 1,250 m apart), resulting in 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 post-LGM unit (Maps A, C) was generated by adding the thickness data to water depths determined by multibeam bathymetry (see sheet 1).

The thickness of uppermost Pleistocene and Holocene sediments in the shelf areas of the Monterey Canyon and Vicinity map area ranges from 0 to 32 m (Map B on sheet 9), and the depth to the unconformity at the base of this unit ranges from less than 10 m in the nearshore to more than 100 m along the rim of Monterey Canyon (Map A). Mean sediment thickness for the shelf areas of the map area is 7.3 m, and the total sediment volume in these areas is $1{,}480\times10^6$ m^3 (table 7–1). Mean sediment thickness south of Monterey Canyon (10.0 m) is about three times greater than mean thickness north of the canyon (2.9 m).

The thickest sediment in the map area (about 32 m) is found in a depocenter south of Monterey Canyon, at water depths of between 10 and 30 m, offshore of the mouth of the Salinas River (Map B).

The Salinas River is the second largest coastal watershed in California (10,800 km^2) and is a significant sediment source (Farnsworth and Warrick, 2007). The depocenter is a prominent, shore-parallel, elongate (about 4 km long and 2 km wide) bar that forms a mound above a uniformly offshore dipping (about 1.5°) basement surface (Map A). The geometry of reflections on seismic-reflection profiles (fig. 1 on sheet 9; figs. 8, 10, 11 on sheet 8) indicates both vertical aggradation and low-angle seaward progradation. Bar morphology and internal structure are consistent with depositional patterns outlined by Wright (1977) for wave-dominated river mouths. Sediment cover thins gradually away from this delta-mouth bar to the south and west, and bedrock is exposed along the rim of Monterey Canyon to the west. The head of Monterey Canyon bounds the north flank of the delta-mouth bar, consistent with the hypothesis that a significant part of the sediment load of the Salinas River is transported down Monterey Canyon (Johnson and others, 2001).

No comparable delta-mouth bar is present offshore of the mouth of the smaller Pajaro River (watershed of 3,400 km^2) north of Monterey Canyon, where the thickest sediment (about 14 m) in this part of the map area is found on the south flank of a shallow, west-trending paleochannel (Map D). Sediment cover thins on the shelf to the south and west, where bedrock is exposed locally on the flanks of Monterey Canyon and Soquel Canyon, respectively.

Six 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 Soquel Canyon) were excluded from this analysis because available seismic-reflection data are insufficient to map sediment distribution in this extremely variable environment.

(1) The southern Monterey Bay domain is bounded by the Monterey Bay shoreline on the south and east, the Monterey Canyon on the north, and the limit of California’s State Waters on the west. Sediment derived from the Salinas River forms a large, shore-parallel, subaqueous delta (thickness of as much as 32 m) that progrades across a thinly sediment-mantled bedrock shelf. Small changes in sediment thickness on the shelf are controlled by irregular bedrock relief that is at least partly attributable to the Monterey Bay Fault Zone (Greene, 1990).

(2) 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 of the two (northern and southern) Monterey Bay domains. 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 with 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.

(3) 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 Monterey Bay domains to the south. 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.

(4) 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 attributed to its semiprotected (from erosive wave energy) location on the south flank of Point Año Nuevo.

(5) 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).

(6) 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 1–6), as well as in Monterey Canyon and Vicinity map area.

Regional sediment-thickness domains in Pigeon Point to southern Monterey Bay region			
	Area (km²)	**Mean sediment thickness (m)**	**Sediment volume (10⁶ m³)**
Entire Pigeon Point to southern Monterey Bay region	849	6.7	5,708
(1) Southern Monterey Bay	253	6.2	1,555
(2) Northern Monterey Bay	307	6.7	2,065
(3) Davenport shelf	134	8.3	1,113
(4) Waddell Creek delta	29	7.8	224
(5) Año Nuevo shelf	58	2.6	154
(6) Pigeon Point shelf	68	8.8	598
Sediment thickness in Monterey Bay and Vicinity map area			
Entire Monterey Bay and Vicinity map area	202	7.3	1,480
Map area within southern Monterey Bay domain	126	10.0	1,261
Map area within northern Monterey Bay domain	75	2.9	219

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

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Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Monterey Canyon and Vicinity map area from approximate Mean High Water (MHW) across the continental shelf, as well as in Monterey Canyon to a water depth of about 1,750 m. This map area includes much of central Monterey Bay, extending just 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 National Oceanic and Atmospheric Administration's Shoreline Data Explorer, is based on their analysis of lidar data (National Geodetic Survey, 2013). Offshore geologic units were delineated on the basis of integrated analyses of adjacent onshore geology with multibeam bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8). 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 areas and 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. With this standard technique, areas and percentages for units containing steep canyon walls are underestimated, whereas areas and percentages for flatter regions (for example, shelf units) are overestimated.

The onshore geology was compiled from Wagner and others (2002) and Graymer and others (2006); 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 Monterey Canyon and Vicinity map area contains two major geomorphic features, (1) the continental shelf, and (2) Monterey Canyon and its tributaries (the Monterey Canyon "system," including Soquel Canyon). The continental shelf in the map area is relatively flat and is characterized by a variably thick (and locally absent) cover of uppermost Pleistocene and Holocene sediment that overlies Neogene bedrock, as well as the Pleistocene undivided paleochannel and canyon-fill deposits (Qcf). Inner shelf and nearshore deposits are mostly sand (Qms), and they are thickest (as much as 32 m) in a shore-parallel bar that extends to the mouth of the Salinas River (see sheet 9). Slope failures off of the west flank of this delta-mouth bar have resulted in three east-west-trending, elongate sandy lobes (Qmsl); individual lobes, which are as much as 3,000 m long and 800 m wide, have as much as 150 cm of relief above the surrounding smooth seafloor, and they commonly are transitional to upslope chutes. Unit Qmsf, which lies offshore of unit Qms in the midshelf area, primarily consists of mud and muddy sand, and it commonly is extensively bioturbated. Sediment cover typically thins in the offshore direction and also toward Monterey Canyon (sheet 9); both the Pleistocene undivided paleochannel and canyon-fill deposits (Qcf) and the upper Miocene and Pliocene Purisima Formation (Tp; Powell and others, 2007) are exposed on the outer shelf and along the rims of the present-day Monterey Canyon system. Both the Purisima Formation and the Pleistocene undivided paleochannel and canyon-fill deposits 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 Qmsf/Tp or Qmsf/Qcf, 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.

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. Sea-level rise was apparently not steady, leading to development of pairs of shoreline angles and adjacent submerged wave-cut platforms (Kern, 1977) during pulses of relative stability. Latest Pleistocene paleoshorelines are best preserved along the flanks of Soquel Canyon, where three sets of wave-cut platforms (Qwp1, Qwp2, Qwp3) and paired risers (Qwpr1, Qwpr2, Qwpr3) are bounded by shoreline angles at water depths of about 120 to 125 m, about 108 m, and about 96 to 100 m, respectively.

Within the Monterey Canyon system, geologic and geomorphic units are delineated and characterized on the basis of multibeam bathymetry (sheet 1), acoustic backscatter (sheet 3), published seafloor-sediment and rock samples (Stakes and others, 1999; Paull and others, 2005a,b, 2010), and previously published descriptions of geology within the submarine-canyon system (see, for example, Greene, 1977; Barry and others, 1996; Wagner and others, 2002), as well as, where available, seismic-reflection profiles (sheet 8) and video observations (sheet 6). Major geologic and geomorphic features within the submarine canyons include the canyon-head area, canyon axial channels, canyon walls, and canyon benches and platforms.

The canyon-head area of Monterey Canyon includes sandy channel fill (Qchc; Paull and others, 2005a), as well as sediment-draped interchannel ridges (Qchr) that are inferred to have formed largely by erosion of the canyon head into older canyon and (or) channel-fill deposits. A geomorphic gradational transition exists from canyon-head channel fill (Qchc) downcanyon to proximal active axial-channel fill (Qcpcf); in addition, both channel-fill units include dynamic, crescent-shaped sandy bedforms (Paull and others, 2005a, 2010; Smith and others, 2005; Xu and others, 2008).

Beyond the canyon-head area, the axial channel of Monterey Canyon forms a sinuous ribbon of coarse-grained deposits (Qccf3) that slopes about 3.5° to the west edge of the map area (Greene and others, 2002; Paull and others, 2005a, 2010; Xu and others, 2008). Xu and others (2002, 2008, 2013) and Paull and others (2010) documented modern sediment-gravity flows down the Monterey Canyon axial channel, indicating that it is an active conduit of sediment transport.

Adjacent to the axial channel are canyon walls, benches, and landslides. Canyon walls that are relatively smooth are generally covered by muddy Quaternary sediments (Qmscw) (Paull and others, 2005a, 2010), whereas steeper and rougher segments of canyon walls commonly contain exposures of bedrock or incised Pleistocene paleochannel and canyon-fill deposits (Qcfcw). Outcrops of the Purisima Formation (here, mapped as unit Tpcw) are found in the upper canyon walls. At greater depths along canyon walls, older, underlying bedrock units (Greene, 1977; Barry and others, 1996; Stakes and others, 1999; Wagner and others, 2002) are exposed. These older units include the Miocene Monterey Formation (Tmcw), the undivided Oligocene or Miocene sandstone unit (Tscw), the undivided Cretaceous and Tertiary bedrock unit (TKvcw), and the Cretaceous granitic rocks of Monterey (Kgrcw). Exposures of these bedrock units and the (incised) undivided Pleistocene paleochannel and canyon-fill deposits (Qcfcw) in the canyon walls are inferred to result from a combination of erosion by dense sediment flows down the axial channel and continuing landslide failure of the canyon walls.

Relatively flat areas immediately adjacent to the axial channel or within the canyon walls are mapped as inner bench deposits (Qcb2) and outer bench deposits (Qcb1), respectively (the term “bench” is from Paull and others [2010] and Maier and others [2012]). Benches generally have lower slopes than surrounding canyon walls and, thus, can accumulate fine-grained sediments, including muddy marine, hemipelagic, turbidite, and landslide deposits (Paull and others, 2005a, 2010). Relatively flat, smooth, sediment-covered platforms on the crests of bathymetric divides between canyon meanders are mapped as canyon platform deposits (Qmscp).

Areas of the canyon walls that are characterized by steep, scallop-shaped scarps and paired hummocky mounds are mapped as landslide deposits (Qlsm). Multiple generations of landslide deposits are mapped (units Qlsm1, Qlsm2, and Qlsm3 are first, second, and third generation, respectively) where failure of older landslide deposits has yielded younger landslide deposits. Paull and others (2005b) noted that landslide scarps commonly are associated with chemosynthetic biological communities.

Landslide blocks in the Monterey Canyon system (Qlsmb) are distinguished by positive relief and deflection of an axial channel. Landslide blocks are inferred to consist of bedrock that is similar to bedrock found in the adjacent canyon walls. One particular block (Qlsmb1), informally named “Navy Slump” (see fig. 1–2), in the distal (within the map area) part of the Monterey Canyon system has been identified as consisting of Cretaceous granitic rocks (Greene and others, 2002; Paull and others, 2005a).

Soquel Canyon is the most prominent of five mapped tributaries to Monterey Canyon. During the sea-level lowstand about 21,000 years ago, Soquel Creek fed directly into Soquel Canyon, carrying coarse-grained sediment directly to the Monterey Canyon system (see sheet 9). Sea-level rise isolated Soquel Canyon from its paired coastal watershed, and this abandoned tributary canyon is now being filled largely with Holocene hemipelagic sediment. Units in the Soquel Canyon axial channel are divided on the basis of the lithology of the fill deposits. In upper Soquel Canyon, the abandoned submarine-canyon axial-channel fill unit (Qccf2) consists of fine-grained sediment. In lower Soquel Canyon adjacent to Monterey Canyon, the abandoned submarine-canyon axial-channel fill unit (Qccf1) contains gravel, sand, and mud (Stakes and others, 1999) possibly derived from Holocene and Pleistocene landslide deposits, and it may also contain bedrock exposures.

Two other abandoned canyon tributaries likely were connected to the Pajaro River during the sea-level lowstand. These two tributaries are mapped (Qctf1) east of Soquel Canyon on the north flank of Monterey Canyon. Another abandoned tributary, mapped (Qctf2) on the south flank of Monterey Canyon, appears to have been connected to the Salinas River during the sea-level lowstand.

In the Monterey Canyon and Vicinity map area, the shelf north and south of Monterey Canyon 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 (sheet 8). Seismic-reflection profiles that traverse this diffuse zone cross as many as nine faults over a width of about 8 km (see, for example, fig. 7 on sheet 8). The 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 locally appear to disrupt 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.

Mapping fault strands in the Monterey Bay Fault Zone across the Monterey Canyon system is problematic. The combination of steep relief, increased water depths, and massive to poorly stratified sediment fill generally results in poor quality of both high-resolution and deeper seismic-reflection profiles (sheet 8). High-resolution bathymetry does not reveal obvious tectonic landforms such as fault lineaments or scarps, likely owing to (1) deformation being distributed across a broad zone, (2) minimal late Quaternary deformation, and (3) active canyon processes. It is important to realize that the Monterey Bay Fault Zone almost certainly crosses the Monterey Canyon system and that the pattern of faulting likely is similar to what is observed on the continental shelf north and south of the canyon; however, this is not shown on the geologic map (sheet 10) or on structure maps (see Maps A, B, E on sheet 9) because conclusive evidence for the locations of individual fault strands within the submarine-canyon system is lacking.

On a regional scale, the Monterey Bay and Vicinity map area lies within a northward-narrowing zone between the San Andreas Fault Zone (about 34 km east of the map area) and the San Gregorio Fault Zone (about 5 km west of the map area), two major structures in the right-lateral transform-fault plate boundary between the North American and Pacific plates. Deformation associated with the Monterey Bay Fault Zone and other structures in the map area accommodates strain that results from this dynamic tectonic setting.

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

Map Unit	Area (m²)	Area (km²)	Percent of total area
Marine shelf sedimentary units			
af	95,563	0.1	0.0
Qms	63,922,337	63.9	15.5
Qmsd	911,555	0.9	0.2
Qmsc	21,764	0.0	0.0
Qmsf	134,040,171	134.0	32.4
Qmsl	2,982,493	3.0	0.7
Qwp1	2,385	0.0	0.0
Qwp2	214,929	0.2	0.1
Qwp3	319,867	0.3	0.1
Qwpr1	3,153	0.0	0.0
Qwpr2	90,970	0.1	0.0
Qwpr3	47,087	0.0	0.0
Total, shelf sedimentary units	202,652,274	202.7	49.0
Marine shelf bedrock and (or) shallow-bedrock units			
Qmsf/Qcf	591,149	0.6	0.1
Qmsf/Tp	11,246,355	11.2	2.8
Qcf	889,548	0.9	0.2
Tp	14,619,693	14.6	3.5
Total, shelf bedrock units	27,346,745	27.3	6.6
Marine submarine-canyon sedimentary units			
Qchc	183,515	0.2	0.0
Qchr	90,800	0.1	0.0
Qcpcf	228,690	0.2	0.1
Qccf3	8,831,497	8.8	2.1
Qccf2	1,119,382	1.1	0.3
Qcb2	2,510,198	2.5	0.6
Qcb1	3,022,380	3.0	0.7
Qmscp	4,340,048	4.3	1.1
Qccf1	349,089	0.3	0.1
Qmscw	65,909,449	65.9	15.9
Qctf2	499,893	0.5	0.1
Qctf1	8,404,028	8.4	2.0
Qlsm	11,428,667	11.4	2.8

Table 8–1. Areas and relative proportions of offshore geologic map units in Monterey Canyon and Vicinity map area.—Continued

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine submarine-canyon sedimentary units—Continued			
Qlsm3	58,149	0.1	0.0
Qlsm2	478,104	0.5	0.1
Qlsm1	855,912	0.9	0.2
Qlsmb	819,795	0.8	0.2
Qlsmb1	946,663	0.9	0.2
Qcfcw	3,319,611	3.3	0.8
Total, canyon sedimentary units	113,395,869	113.4	27.4
Marine submarine-canyon bedrock			
Tpcw	25,216,790	25.2	6.1
Tmcw	15,147,087	15.1	3.7
Tscw	2,804,529	2.8	0.7
TKvcw	2,156,279	2.2	0.5
Kgcw	24,539,737	24.5	5.9
Total, canyon bedrock units	69,864,422	69.9	16.9
Total Monterey Bay and Vicinity map area	413,259,310	413.3	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, Qmsf/Tp indicates that thin sheet of Qmsf overlies Tp)]

NEARSHORE, SHELF, AND CANYON RIM

af **Artificial fill (late Holocene)**—Rock, sand, and mud; placed and (or) dredged; associated with Moss Landing Harbor; also includes wastewater-outfall pipe

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 on north flank of Monterey Canyon, about 500 to 2,500 m west of Moss Landing. 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, gravel, cobbles, and possibly boulders; recognized primarily 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
Qmsl	**Marine shelf sediment lobes (late Holocene)**—Three predominantly sandy lobes of recently mobilized marine sediments; derived from west flank of shore-parallel bar at mouth of Salinas River (see sheets 8, 9). Individual lobes are as much as 3,000 m long and 800 m wide, and they have as much as 150 cm of relief above surrounding smooth seafloor; lobes are elongate approximately perpendicular to shoreline
Qwp3	**Submerged wave-cut platform, about 96 to 100 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Present only on west flank of head of Soquel Canyon. Platform is as wide as 400 m and can be continuously traced laterally for more than 1,000 m; bounded upslope by paleoshoreline angle (Kern, 1977) and platform riser (Qwpr3). Shallowest and youngest of three platforms; inferred to have been formed by wavecutting, in periods of relative sea-level stillstands during overall sea-level rise following Last Glacial Maximum (Stanford and others, 2011)
Qwpr3	**Submerged wave-cut platform riser, base about 96 to 100 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Present only on west flank of head of Soquel Canyon. Smooth, offshore-dipping surface as wide as 55 m; 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 (Qwp3).
Qwp2	**Submerged wave-cut platform, about 108 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Platform is as wide as 230 m, dips gently offshore, and can be continuously traced laterally for about 800 m; bounded upslope by paleoshoreline angle (Kern, 1977) and platform riser (Qwpr2). Second of three platforms; inferred to have been formed by wavecutting, in periods of relative sea-level stillstands during overall sea-level rise following Last Glacial Maximum (Stanford and others, 2011)
Qwpr2	**Submerged wave-cut platform riser, base about 108 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Smooth, offshore-dipping surface as wide as about 50 m; lower contact is paleoshoreline angle (Kern, 1977). Represents paleo–sea cliff or onshore slope associated with development of wave-cut platform (Qwp2)
Qwp1	**Submerged wave-cut platform, about 120 to 125 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Platform is as wide as 40 m, dips gently offshore, and can be traced laterally for as much as 125 m; bounded upslope by paleoshoreline angle (Kern, 1977) and platform riser (Qwpr1). Deepest and oldest of three platforms; inferred to have been formed by wavecutting, in periods of relative sea-level stillstands during overall sea-level rise following Last Glacial Maximum (Stanford and others, 2011)
Qwpr1	**Submerged wave-cut platform riser, base about 120 to 125 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment. Smooth, offshore-dipping surface as wide as about 25 m; lower contact is paleoshoreline angle (Kern, 1977). Represents paleo–sea cliff or onshore slope associated with development of wave-cut platform (Qwp1)

Qcf	**Paleochannel and canyon-fill deposits, undivided (Pleistocene)**—Large-scale scour-and-fill deposits that extend west from mouth of Pajaro River into Monterey Canyon system; inferred to have formed mainly by erosive fluvial and submarine-canyon erosion during Quaternary sea-level lowstands and subsequent channel-filling with fluvial, eolian, and marine deposits; found on shelf and along submarine canyon rims. Stippled areas (composite unit Qmsf/Qcf) indicate where thin sheets of Qmsf overlie unit
Tp	**Purisima Formation, undivided (Pliocene and late Miocene)**—Thick-bedded, tuffaceous and diatomaceous siltstone that contains thick interbeds of fine-grained sandstone; found on shelf and along submarine-canyon rims. Stippled areas (composite unit Qmsf/Tp) indicate where thin sheets of Qmsf overlie unit

SUBMARINE CANYON

Channels

Qchc	**Submarine-canyon-head channel deposits (late Holocene)**—Primarily sand; characterized by dendritic pattern and crescent-shaped bedforms; found within 500 m of modern shoreline
Qchr	**Submarine-canyon-head interchannel ridges (late Holocene)**—Probably semiconsolidated sand and mud; extends above adjacent submarine-canyon head (Qchc) into proximal active axial channel (Qcpcf)
Qcpcf	**Proximal active submarine-canyon axial-channel fill (late Holocene)**—Primarily sand; found in upper Monterey Canyon; characterized by crescent-shaped bedforms
Qccf3	**Active submarine-canyon axial-channel fill (late Holocene)**—Sand and gravel; may contain minor bedrock outcrops and landslide deposits; found in Monterey Canyon; characterized by curvilinear form and crescent-shaped bedforms
Qccf2	**Abandoned submarine-canyon axial-channel fill (Holocene)**—Marine and hemipelagic mud; found in upper Soquel Canyon; draped by marine and hemipelagic sediments after isolation of submarine-canyon head from terrestrial-sediment sources during Quaternary sea-level rise
Qccf1	**Abandoned submarine-canyon axial-channel fill (Holocene and Pleistocene)**—Gravel, sand, and mud; found in lower Soquel Canyon; deposits other than hemipelagic mud likely result from landslide failures along submarine-canyon walls; may include bedrock exposures

Walls

Qcb2	**Submarine-canyon inner bench deposits (Holocene)**—Mud and sand; found in areas of lower gradient adjacent to axial channel that accumulate dominantly fine-grained sediments; commonly includes hemipelagic, turbidite, and landslide deposits; undifferentiated origin, possibly related to incision of older submarine-canyon and (or) channel deposits and (or) accumulation of landslide, turbidite, and hemipelagic deposits
Qcb1	**Submarine-canyon outer bench deposits (Holocene and Pleistocene)**—Mud and minimal sand; found in areas of lower gradient that accumulate dominantly muddy hemipelagic and turbidite deposits within submarine-canyon-wall deposits (Qmscw); undifferentiated origin, possibly related to incision of older submarine-canyon and (or) channel deposits and (or) accumulation of landslide, turbidite, and hemipelagic deposits

Qmscp	**Submarine-canyon platform deposits (Holocene and Pleistocene)**—Mud and minimal sand; found in relatively smooth areas of lower gradient on crests of bathymetric divides between submarine-canyon meanders
Qmscw	**Submarine-canyon-wall deposits (Holocene and Pleistocene)**—Inferred to be draped by marine and hemipelagic mud and fine-grained turbidite deposits; may include minor bedrock outcrops and landslide deposits; submarine-canyon walls slope toward axial channel (Qcpcf, Qccf1, Qccf2, Qccf3) or benches (Qcb1, Qcb2)
Qcfcw	**Paleochannel and canyon-fill deposits, undivided (Pleistocene)**—Large-scale scour-and-fill deposits that extend west from mouth of Salinas River into Monterey Canyon system; inferred to have formed mainly by erosive fluvial and submarine-canyon erosion during Quaternary sea-level lowstands and subsequent channel-filling with fluvial, eolian, and marine deposits; found within submarine-canyon walls
Tpcw	**Purisima Formation, undivided (Pliocene and late Miocene)**—Thick-bedded, tuffaceous, and diatomaceous siltstone that contains thick interbeds of fine-grained sandstone; found within submarine-canyon walls
Tmcw	**Monterey Formation (Miocene)**—Thin-bedded, siliceous and calcareous mudstone and shale interbedded with arkosic sandstone; found within submarine-canyon walls
Tscw	**Sandstone, undivided (Miocene or Oligocene)**—Sandstone; possibly correlative with the Vaqueros Formation or the Santa Margarita Formation; stratigraphically below sandstones of the Purisima Formation (Tpcw) in submarine-canyon walls near confluence of Soquel Canyon and Monterey Canyon (Stakes and others, 1999); may also be correlative with the Lompico Formation or basal section of the Monterey Formation
TKvcw	**Tertiary and Cretaceous bedrock, undivided (Tertiary and Cretaceous)**—Complex, mixed lithologies of intrusive volcanic rocks and sedimentary host rocks, as well as Cretaceous granitic rocks; found in walls of Soquel Canyon (Stakes and others, 1999)
Kgrcw	**Granitic rocks of Monterey (Cretaceous)**—Granitic rocks; found within submarine-canyon walls

Landslide Deposits

Qlsm	**Landslide deposits, marine, undivided (Holocene and Pleistocene)**—Inferred to consist of lithologies similar to that of adjacent submarine-canyon walls. Scarps, chutes, and lobes, located primarily in, or adjacent to, submarine-canyon walls. Scarps typically form steep, concave surfaces; lobes form hummocky mounds
Qlsm3	**Landslide deposits, marine, third generation (Holocene and Pleistocene)**—Inferred to consist of lithologies similar to that of adjacent submarine-canyon walls. Scarps, chutes, and lobes, located primarily in, or adjacent to, submarine-canyon walls. Scarps typically form steep, concave surfaces; lobes form hummocky mounds. Youngest of three divided landslide-deposit units; derived from second-generation landslide deposits (Qlsm2)
Qlsm2	**Landslide deposits, marine, second generation (Holocene and Pleistocene)**—Inferred to consist of lithologies similar to that of adjacent submarine-canyon walls. Scarps, chutes, and lobes, located primarily in, or adjacent to, submarine-canyon walls. Scarps typically form steep, concave surfaces; lobes form hummocky mounds. Derived from first-generation landslide deposits (Qlsm1)
Qlsm1	**Landslide deposits, marine, first generation (Holocene and Pleistocene)**—Inferred to consist of lithologies similar to that of adjacent submarine-canyon walls. Scarps, chutes, and lobes, located primarily in, or adjacent to, submarine-canyon walls.

Scarps typically form steep, concave surfaces; lobes form hummocky mounds. Mapped in areas where unit is source of younger landslide deposits (Qlsm2)

Qlsmb	**Landslide blocks, marine, undivided (Holocene and (or) Pleistocene)**—Commonly bedrock; found in submarine-canyon system; characterized by positive relief and deflection of submarine-canyon axial channel
Qlsmb1	**Granitic-rock blocks (Holocene and (or) Pleistocene)**—Consists of blocks of Cretaceous granitic rocks; characterized by positive relief and deflection of submarine-canyon axial channel; may be landslide block; commonly referred to as “Navy Slump” (Greene and others, 2002; Paull and others, 2005a)

Tributary Fill

Qctf2	**Tributary-submarine-canyon fill, Salinas River paleochannel(?) (Holocene and Pleistocene)**—Gravel, mud, and sand, in abandoned tributary submarine canyon on south flank of Monterey Canyon; may include fluvial deposits of ancestral Salinas River
Qctf1	**Tributary-submarine-canyon fill, Pajaro River paleochannels(?) (Holocene and Pleistocene)**—Marine, hemipelagic mud and sand, in abandoned tributary submarine canyons on north flank of Monterey Canyon; may include fluvial deposits of Pajaro River paleochannels, landslide scarps, and landslide deposits

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units compiled from Wagner and others (2002) and Graymer and others (2006); 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)**—Material deposited by humans; includes jetties at entrance to Moss Landing Harbor
Qc	**Stream-channel deposits (late Holocene)**—Sand, silt, and gravel deposits within active stream channels and canals
Qbs	**Beach-sand deposits (late Holocene)**—Fine to very-coarse sand; forms active beaches in coastal environments; may form veneer over bedrock platform. Locally, may include dune-sand deposits too small to show at map scale
Qa	**Alluvial deposits (late Holocene)**—Alluvium deposited adjacent to active stream channels
Qds	**Dune-sand deposits (Holocene)**—Very well-sorted, fine to medium sand; forms both active and stabilized dunes in coastal environments
Qya	**Alluvial deposits, undivided (Holocene)**—Alluvium deposited adjacent to active stream channels; also includes flood-plain deposits of Wagner and others (2002). Locally, may include small marine-terrace and channel deposits too small to delineate at map scale
Qf	**Alluvial fan deposits (Holocene)**—Relatively undissected, unconsolidated, fine-grained, heterogeneous layers of sand, silt, and gravel; deposited by streams emanating from canyons onto alluvial plains; identified primarily by fan morphology and topographic expression
Qb	**Basin deposits (Holocene)**—Unconsolidated, fine-grained sediment; deposited in low-energy environments that include estuaries, lagoons, marsh-filled sloughs, and lakes
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
Qe	**Eolian sand (Holocene)**—Very well-sorted, fine to medium sand
Qt	**Stream-terrace deposits (Holocene and Pleistocene)**—Sand, gravel, silt, and minor clay of uncertain age; underlies relatively flat ridges that are elevated above stream channels
Qls	**Landslide deposits (Holocene and Pleistocene)**—Weathered and disintegrated rocks and soil; physically weathered
Qtw	**Terrace deposits of Watsonville terrace (Pleistocene)**—Undivided fluvial and alluvial fan facies of semiconsolidated, moderately to poorly sorted silt, sand, clay, and gravel
Qmt2	**Lowest emergent marine-terrace deposits (Pleistocene)**—Semiconsolidated sand and less common gravel deposits, on uplifted marine-abrasion platforms along coast. Locally, may include fluvial and (or) sand-dune deposits that are too small or numerous to delineate at map scale; in addition, commonly contains nondelineated eolian deposits
Qmt1	**Marine-terrace deposits, undivided (Pleistocene)**—Semiconsolidated sand and less common gravel deposits, on uplifted marine-abrasion platforms along coast; colluvial material commonly spills out on back (landward) side of platform; locally, may include fluvial and (or) colluvial deposits that are too small or numerous to delineate at map scale; found at elevations higher than that of Qmt2
Qods	**Older dune-sand deposits (Pleistocene)**—Very well-sorted, fine to medium sand; forms mounded topography on elevated platforms
Qar	**Aromas Sand, undivided (Pleistocene)**—Heterogeneous unit of mainly eolian and fluvial sand, silt, clay, and gravel
Qae	**Eolian lithofacies (Pleistocene)**—Moderately well-sorted eolian sand
Qof	**Alluvial fan deposits (Pleistocene)**—Highly dissected and extensive alluvial fan deposits

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