California State Waters Map Series—Offshore of Pigeon Point, California

By Guy R. Cochrane, Janet T. Watt, Peter Dartnell, H. Gary Greene, Mercedes D. Erdey, Bryan E. Dieter, Nadine E. Golden, Samuel Y. Johnson, Charles A. Endris, Stephen R. Hartwell, Rikk G. Kvitek, Clifton W. Davenport, Lisa M. Krigsman, Andrew C. Ritchie, Ray W. Sliter, David P. Finlayson, and Katherine L. Maier

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

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Preface

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

The CSMP approach is to create highly detailed seafloor maps through collection, integration, interpretation, and visualization of swath sonar bathymetric data (the undersea equivalent of satellite remote-sensing data in terrestrial mapping), acoustic backscatter, seafloor video, seafloor photography, high-resolution seismic-reflection profiles, and bottom-sediment sampling data. The map products display seafloor morphology and character, identify 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 3-nautical-mile (5.6-km) limit of California's State Waters. Unfortunately, surveying the zone from MHHW out to 10-m water depth is not consistently possible using ship-based surveying methods, owing to sea state (for example, waves, wind, or currents), kelp coverage, and shallow rock outcrops. Accordingly, some of the maps presented in this series commonly do not cover the zone from the shore out to 10-m depth; these "no data" zones appear pale gray on most maps.

This map is part of a series of online U.S. Geological Survey (USGS) publications, each of which includes several map sheets, some explanatory text, and a descriptive pamphlet. Each map sheet

[1] U.S. Geological Survey
[2] Moss Landing Marine Laboratories, Center for Habitat Studies
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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.

[6] Environmental Systems Research Institute, Inc.

Chapter 1. Introduction

By Guy R. Cochrane

Regional Setting

The map area offshore of Pigeon Point, California, which is referred to herein as the “Offshore of Pigeon Point” map area (figs. 1–1, 1–2), is located in central California, on the Pacific Coast, 50 km south of San Francisco and 25 km northwest of Santa Cruz. The onshore part of the Offshore of Pigeon Point map area is sparsely populated. The nearest significant onshore cultural center is Pescadero, an unincorporated community with a population of well under 1,000 that lies about 2 km north of the map area. A large percentage of coastal land in the map area is incorporated in parks and open-space trusts. The hilly coastal area is virtually undeveloped, used primarily for agricultural or as grazing land for sheep and cattle. Agriculture is limited to the coastal uplifted Pleistocene marine terraces and upper Pleistocene alluvial fan deposits (see sheet 10), which lie between the shoreline and the northwest-trending Santa Cruz Mountains (fig. 1–1), part of the California Coast Ranges.

The Offshore of Pigeon Point map area is cut by the San Gregorio Fault Zone (fig. 1–2) and is located a few kilometers southwest of the San Andreas Fault Zone (see fig. 1–1; see also, California Geological Survey, 2002). The San Andreas Fault Zone is the most important structure within the Pacific–North American plate boundary, the only continental margin in the world delineated largely by transform faults (Dickinson, 2004). Coastal uplift and folding in the Offshore of Pigeon Point map area has been attributed to a westward bend in the San Andreas Fault Zone and also to right-lateral movement along the San Gregorio Fault Zone (Anderson and Menking, 1994). The irregular coastal geomorphology of this area, which consists of low, rocky cliffs and sparse, small pocket beaches backed by low, terraced hills (Griggs and others, 2005), is partly attributable to this ongoing deformation.

The offshore part of the Offshore of Pigeon Point map area primarily consists of relatively flat and shallow continental shelf. The shelf dips gently (less than 1°) seaward, so that water depths at the 3-nautical-mile (5.6-km) limit of California’s State Waters range from about 65 to about 75 m. The shelf break, which lies approximately 20 to 26 km from the shoreline, is incised by the heads of two submarine canyons, which extend well into the outer continental shelf area about 6 to 10 km south-southwest of Point Año Nuevo (see fig. 1–1). At water depths of about 130 m, the shelf break approximates the shoreline during the sea-level lowstand of the Last Glacial Maximum (LGM), about 21,000 years ago (see, for example, Stanford and others, 2011).

The shelf in the Offshore of Pigeon Point map area is underlain by variable amounts (0 to 20 m) of upper Quaternary nearshore and shelf sediments deposited during the post-LGM sea-level rise (see sheet 9). The thickest deposits, which are located in the northern part of the area, are probably derived from Pescadero Creek, a large coastal watershed that enters the Pacific Ocean about 3 km north of the map area, as well as from Arroyo de los Frijoles, which is presently obstructed by the Lake Lucerne Dam near Bean Hollow State Beach (fig. 1–2). The shelf in the southern part of the map, which lacks sediment supply (likely owing to its distance from large coastal watersheds), is characterized by the presence of uplifted bedrock that has been linked to a local zone of transpression in the San Gregorio Fault Zone (Weber, 1990). This uplift, coupled with high wave energy, has resulted in little or no sediment cover in the south where exposures of bedrock are present at water depths of as much as 45 m.

This part of central California is exposed to large North Pacific swells from the northwest throughout the year. North Pacific swell heights range from 2 to 10 m, the larger swells occurring from October to May (Storlazzi and Wingfield, 2005). During El Niño–Southern Oscillation (ENSO) events, winter storms track farther south than they do in normal (non-ENSO) years, thereby impacting the map area more frequently and with waves of larger heights (Storlazzi and Wingfield, 2005). Bedrock exposed along the coast consists of erosion-resistant sedimentary rocks, and significant erosion events primarily are restricted to storm-wave activity that also erodes the overlying unconsolidated marine-terrace sediments (Griggs and others, 2005).

Coastal sediment transport in the Offshore of Pigeon Point map area is characterized by north-to-south littoral transport of sediment that is derived mainly from streams in the Santa Cruz Mountains and also from local coastal erosion (Hapke and others, 2006). Shoreline-change studies indicate long-term erosion; within the region between San Francisco and Davenport, the highest long- and short-term coastal-erosion rates (-1.8 and -2.6 m/y, respectively) occur in the map area, just north of Point Año Nuevo (Hapke and others, 2006) (fig. 1–1). During the last approximately 300 years, as much as 18 million cubic yards (14 million cubic meters) of sand-sized sediment has been eroded from the area between Año Nuevo Island and Point Año Nuevo and transported south (Griggs and others, 2005). Once widened by this pulse of eroded sediment, beaches south of Point Año Nuevo are now narrowing as the tail end of this mass of eroded sand progresses farther south (Griggs and others, 2005).

Seafloor habitats in the Offshore of Pigeon Point map area (see sheet 7 of this report) lie within the Shelf (continental shelf) megahabitat of Greene and others (1999). Significant rocky outcrops, which support kelp-forest communities in the nearshore and rocky-reef communities in deeper water, dominate the inner shelf waters, except for a few sand-filled paleochannels offshore of coastal creeks. In the outer shelf, habitats grade seaward from sand to fine-grained sand and mud. Offshore of Pigeon Point, an extensive area of depressions, which are caused by current scour, extends out to 50 m water depth (see sheet 3).

Benthic species observed in the Offshore of Pigeon Point map area are natives of the cold-temperate biogeographic zone that is called either the “Oregonian province” (Briggs, 1974) or the “northern California ecoregion” (Spalding and others, 2007). This biogeographic province is maintained by the long-term stability of the southward-flowing California Current, the eastern limb of the North Pacific subtropical gyre that flows from southern British Columbia to Baja California. At its midpoint off central California, the California Current transports subarctic surface (0–500 m deep) waters southward, about 150 to 1,300 km from shore (Lynn and Simpson, 1987; Collins and others, 2000). Seasonal northwesterly winds (Inman and Jenkins, 1999) that are, in part, responsible for the California Current, generate coastal upwelling. The south end of the Oregonian province is at Point Conception (about 335 km south of the map area), although its associated phylogeographic group of marine fauna may extend beyond to the area offshore of Los Angeles in southern California (Dawson and others, 2006). The ocean off of central California has experienced a warming over the last 50 years that is driving an ecosystem shift away from the productive subarctic regime towards a depopulated subtropical environment (McGowan and others, 1998).

Biological productivity resulting from coastal upwelling supports populations of Sooty Shearwater (*Puffinus griseus*), Western Gull (*Larus occidentalis*), Common Murre (*Uria aalge*), Cassin’s Auklet (*Ptychoramphus aleuticus*), and many other less populous bird species (Ainley and Hyrenbach, 2010). In addition, an observable recovery of Humpback and Blue Whales (*Megaptera novaeangliae* and *Balaenoptera musculus*, respectively) has occurred in the area; both species are dependent on coastal upwelling to provide nutrients (Calambokidis and Barlow, 2004). Año Nuevo State Park is the site of one of the largest mainland breeding colonies in the world for the Northern Elephant Seal (*Mirounga angustirostris*). The large extent of exposed inner shelf bedrock supports large forests of “bull kelp” (*Nereocystis luetkeana*) (Miller and Estes, 1989), which is well adapted for high-wave-energy environments (Koehl and Wainwright, 1977). Common fish species found in the kelp beds and rocky reefs include blue rockfish (*Sebastes mystinus*), black rockfish (*Sebastes melanops*), olive rockfish (*Sebastes serranoides*), kelp rockfish (*Sebastes atrovirens*), gopher rockfish (*Sebastes carnatus*), black-and-yellow rockfish (*Sebastes chrysomelas*), painted greenling (*Oxylebius pictus*), kelp greenling (*Hexagrammos decagrammus*), and lingcod (*Ophiodon elongatus*) (Stephens and others, 2006).

Publication Summary

This publication about the Offshore of Pigeon Point 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 three different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data reveal a range of physiographic features (highlighted in the perspective views on sheet 4) such as the flat, sediment-covered, inner continental to midcontinental shelf, as well as shallow "scour depressions" and local, tectonically controlled bedrock uplifts. To validate geological and biological interpretations of the sonar data shown in sheets 1, 2, and 3, the U.S. Geological Survey towed a camera sled over specific offshore locations, collecting both video and photographic imagery; 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 integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

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

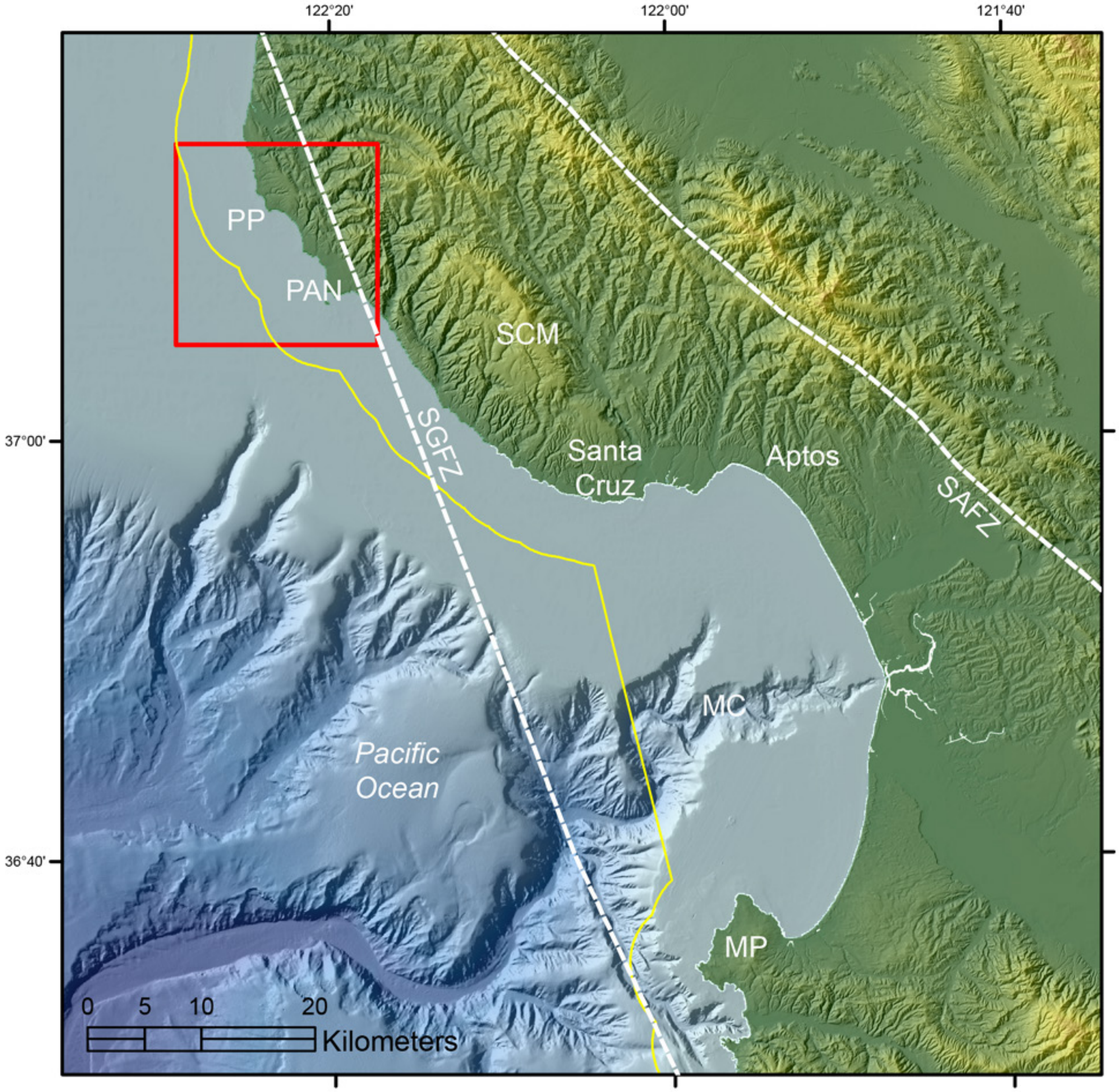

Figure 1–1. Physiography of Pigeon Point to southern Monterey Bay region and its environs. Box shows Offshore of Pigeon Point map area. Yellow line shows limit of California's State Waters. Dashed white lines show traces of San Gregorio Fault Zone (SGFZ) and San Andreas Fault Zone (SAFZ). Other abbreviations: MC, Monterey Canyon; MP, Monterey peninsula; PAN, Point Año Nuevo; PP, Pigeon Point; SCM, Santa Cruz Mountains.

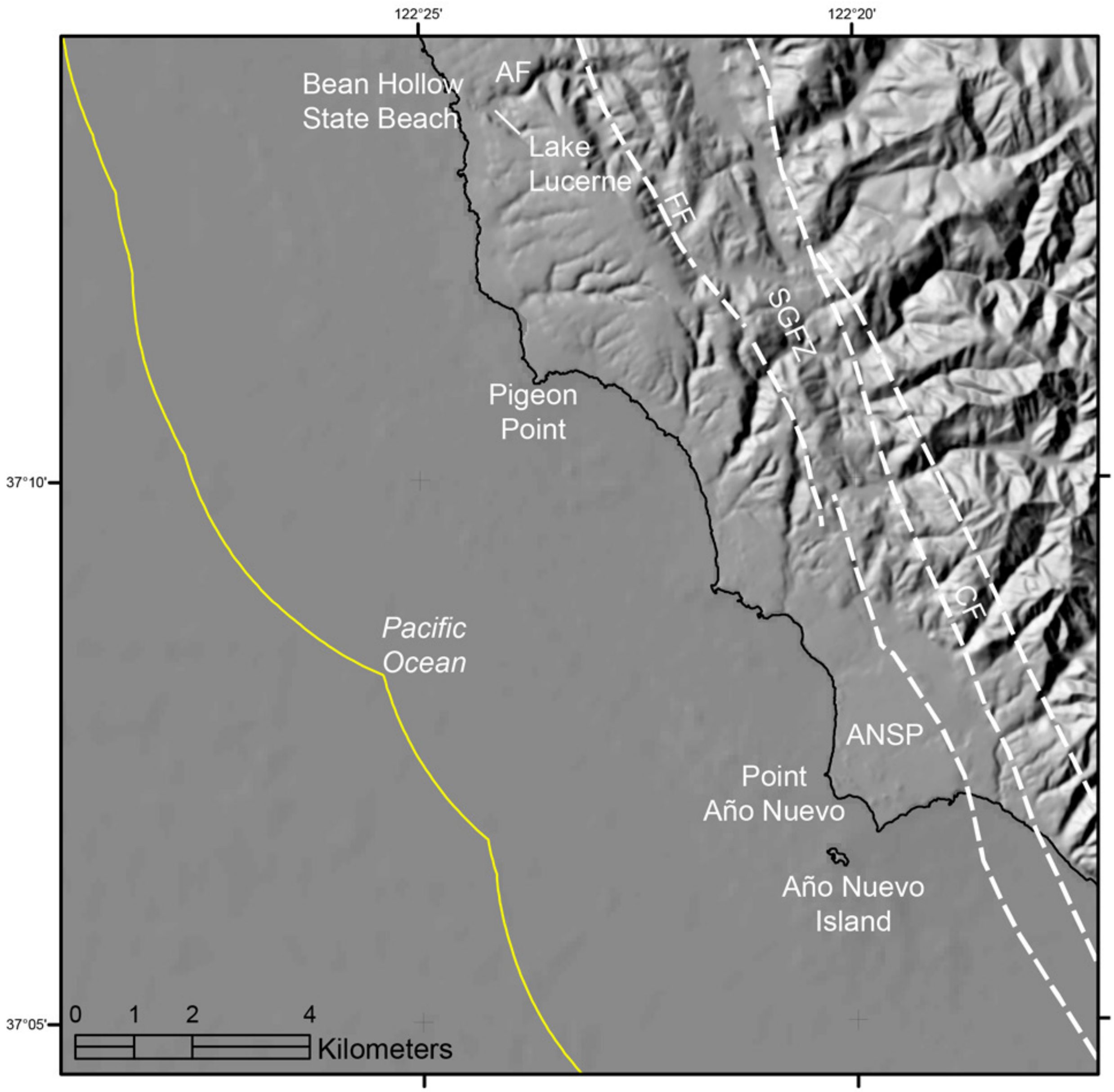

Figure 1–2. Coastal geography of Offshore of Pigeon Point map area. Yellow line shows limit of California's State Waters. Dashed white lines show trace of San Gregorio Fault Zone (SGFZ), including two major strands (Frijoles Fault [FF] and Coastways Fault [CF]). Other abbreviations: AF, Arroyo de los Frijoles; ANSP, Año Nuevo State Park.

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

By Peter Dartnell and Rikk G. Kvitek

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of Pigeon Point map area in central California were generated from bathymetry and backscatter data collected by Fugro Pelagos, by California State University, Monterey Bay (CSUMB), and by the U.S. Geological Survey (USGS) (fig. 1 on sheets 1, 2, 3). Mapping was completed between 2006 and 2009, using a combination of 400-kHz Reson 7125 and 244-kHz Reson 8101 multibeam echosounders, as well as a 234-kHz SWATHplus bathymetric sidescan-sonar system. These mapping missions combined to collect both bathymetry (sheets 1, 2) and acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 3-nautical-mile limit of California's State Waters.

During the Fugro Pelagos and CSUMB mapping missions, an Applanix POS MV (Position and Orientation System for Marine Vessels) was used to accurately position the vessels during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm). To account for tidal-cycle fluctuations, Fugro Pelagos used StarFix HP and XP real-time kinematic (RTK) GPS receivers, and CSUMB used a NavCom 2050 receiver; in addition, sound-velocity profiles were collected with an Applied Microsystems (AM) SVPlus sound velocimeter. Soundings were corrected for vessel motion using the Applanix POS MV data, for variations in water-column sound velocity using the AM SVPlus data, and for variations in water height (tides) using vertical-position data from the RTK receivers. The backscatter data were postprocessed using Geocoder, within which 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 mission, 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 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). The backscatter data were postprocessed using USGS software (D.P. Finlayson, written commun., 2011) that normalizes for time-varying signal loss and beam-directivity differences. Thus, the raw 16-bit backscatter data were gain-normalized to enhance the backscatter of the SWATHplus system. The resulting normalized-amplitude values were rescaled to 16-bit and gridded into GeoJPEGs using GRID Processor Software, then imported into a GIS and converted to GRIDs.

Processed soundings from the different mapping missions were exported from the acquisition or processing software as XYZ files and bathymetric surfaces. All of the surfaces were then merged into one overall 2-m-resolution bathymetric-surface model and clipped to the boundary of the map area.

Difference calculations of the overlapping bathymetry grids showed that there is good agreement (a mean difference of only 0.18 m, with 0.34 m standard deviation) between the 2006–2007 Fugro Pelagos and CSUMB bathymetry data and the overlapping 2009 USGS data, even though the data were collected at different times using different mapping systems.

An illumination having an azimuth of 300° and from 45° above the horizon was then applied to the bathymetric surface to create the shaded-relief imagery (sheets 1, 2). In addition, a modified "rainbow" color ramp was applied to the bathymetry data for sheet 1, using reds to represent shallower depths, and yellows to represent greater depths (note that the Offshore of Pigeon Point map area requires only the shallower part of the full-rainbow color ramp used on some of the other maps in the California State Waters Map Series; see, for example, Kvitek and others, 2012). This colored bathymetry surface was draped over the shaded-relief imagery at 60-percent transparency to create a colored shaded-relief map (sheet 1). Note that the ripple patterns and parallel lines that are apparent within the map area are data-collection and -processing artifacts. In addition, lines at the borders of some surveys are the result of slight differences in depth, as measured by different mapping systems in different years. These various artifacts are made obvious by the hillshading process.

Bathymetric contours (sheets 1, 2, 3, 5, 7, 10) were generated at 10-m intervals from the merged 2-m-resolution bathymetric surface. The merged surface was 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 location). The contours were generated from this smoothed surface 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 mapping system and processing method were merged into their own individual grids. These individual grids, which cover different areas, were displayed in a GIS to create a composite acoustic-backscatter map (sheet 3). On the map, brighter tones indicate higher backscatter intensity, and darker tones indicate lower backscatter intensity. The intensity represents a complex interaction between the acoustic pulse and the seafloor, as well as characteristics within the shallow subsurface, providing a general indication of seafloor texture and composition. Backscatter intensity depends on the acoustic source level; the frequency used to image the seafloor; the grazing angle; the composition and character of the seafloor, including grain size, water content, bulk density, and seafloor roughness; and some biological cover. Harder and rougher bottom types such as rocky outcrops or coarse sediment typically return stronger intensities (high backscatter, lighter tones), whereas softer bottom types such as fine sediment return weaker intensities (low backscatter, darker tones). The differences in backscatter intensity that are apparent in some areas of the map on sheet 3 are due to the different frequencies of the mapping systems, as well as to different processing techniques. Parallel lines of higher backscatter intensity throughout the map area are data-collection and -processing artifacts.

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

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

By Peter Dartnell

Mapping California's State Waters has produced a vast amount of acoustic and visual data, including bathymetry, acoustic backscatter, seismic-reflection profiles, and seafloor video and photography. These data are used by researchers to develop maps, reports, and other tools to assist in the coastal and marine spatial-planning capability of coastal-zone managers and other stakeholders. For example, seafloor-character (sheet 5), habitat (sheet 7), and geologic (sheet 10) maps of the Offshore of Pigeon Point map area may assist in the designation of Marine Protected Areas, as well as in their monitoring. These maps and reports also help to analyze environmental change owing to sea-level rise and coastal development, to model and predict sediment and contaminant budgets and transport, to site offshore infrastructure, and to assess tsunami and earthquake hazards. To facilitate this increased understanding and to assist in product development, it is helpful to integrate the different datasets and then view the results in three-dimensional representations such as those displayed on the data integration and visualization sheet for the Offshore of Pigeon Point 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 yellows represent deeper depths; topographic data were shown in gray shades. Acoustic-backscatter geotiff images also were draped over the bathymetry data. The colored bathymetry, topography, and draped backscatter were then tilted and panned to create the perspective views such as those shown in figures 1, 2, 4, 5, and 6 on sheet 4. These views highlight the seafloor morphology in the Offshore of Pigeon Point map area, which includes exposed outcrops of layered and fractured bedrock and complex patterns of shallow depressions.

Video-mosaic images created from digital seafloor video (for example, fig. 3 on sheet 4) display the geologic complexity (rock, sand, and mud; see sheet 10) and biologic complexity of the seafloor. Whereas photographs capture high-quality snapshots of smaller areas of the seafloor (see sheet 6), video mosaics capture larger areas and can show transition zones between seafloor environments. Digital seafloor video is collected from a camera sled towed approximately 1 to 2 meters 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. 5 on sheet 4). These block diagrams were created by converting digital seismic-reflection-profile data (see sheet 8) into TIFF images, while taking note of the starting and ending coordinates and maximum and minimum depths. The images were then imported into the Fledermaus® software as vertical images and merged with the bathymetry imagery.

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

By Mercedes D. Erdey and Guy R. Cochrane

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

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

The following four substrate classes are identified in the Offshore of Pigeon Point map area:

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

The seafloor-character map of the Offshore of Pigeon Point map area (sheet 5) was produced using video-supervised maximum-likelihood classification of the bathymetry and intensity of return from sonar systems, following the method described by Cochrane (2008). The two variants used in this classification were backscatter intensity and derivative rugosity. The rugosity calculation was performed using the Terrain Ruggedness (VRM) tool within the Benthic Terrain Modeler toolset v. 3.0 (Wright and others, 2012; available at http://esriurl.com/5754).

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

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

The seafloor-character classification also is summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 79.1 percent (104.8 km^2) of the map area: 15.4 percent (20.4 km^2) is in Depth Zone 2, and 63.7 percent (84.4 km^2) is in Depth Zone 3. Mixed smooth sediment (sand and gravel) and rock (that is, sediment typically forming a veneer over bedrock, or rock outcrops having little to no relief) make up 5.7 percent (7.5 km^2) of the map area: 3.5 percent (4.6 km^2) is in Depth Zone 2, and 2.2 percent (2.9 km^2) is in Depth Zone 3. Rock and boulder, rugose (rock and boulder outcrops having high surficial complexity) makes up 13.7 percent (18.1 km^2) of the map area: 10.2 percent (13.5 km^2) is in Depth Zone 2, and 3.5 percent (4.6 km^2) is in Depth Zone 3. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than the surrounding seafloor) makes up 1.5 percent (2.0 km^2) of the map area: 0.3 percent (0.4 km^2) is in Depth Zone 2 and 1.2 percent (1.6 km^2) is in Depth Zone 3.

A small number of video observations were used to supervise the numerical classification of the seafloor. All video observations (see sheet 6) are used for accuracy assessment of the seafloor-character map after classification. To compare observations to classified pixels, each observation point is assigned a class (I, II, or III), according to the visually derived, major or minor geologic component (for example, sand or rock) and the abiotic complexity (vertical variability) of the substrate recorded during ground-truth surveys (table 4–1; see, also, chapter 5 of this pamphlet). Class IV values were assigned on the basis of the observation of one or more of a group of features that includes both larger scale bedforms (for example, sand waves), as well as sediment-filled scour depressions that resemble the “rippled scour depressions” of Cacchione and others (1984) and Phillips and others (2007) and also the “sorted bedforms” of Murray and Thieler (2004), Goff and others (2005), and Trembanis and Hume (2011). On the geologic map (see sheet 10 of this report), they are referred to as “marine shelf scour depressions.”

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

The seafloor in the Offshore of Pigeon Point map area is covered predominantly by Class I sediment composed of soft, unconsolidated sand and mud. Several small exposures of rugose bedrock (Class III) are present in the nearshore area, and a larger area of bedrock outcrop is mapped offshore of

Año Nuevo State Park. The bedrock outcrops are covered with varying thicknesses of fine (Class I) to coarse (Class II) sediment. Several areas of medium- to coarse-grained scour depressions (Class IV) also have been identified adjacent to rock outcrops.

The classification accuracy of Classes I, III, and IV (72 percent, 84 percent, and 98 percent accurate, respectively; table 4–2) is determined by comparing the shipboard video observations and the classified map. The weaker (31 percent accurate) agreement in Class II (mixed smooth sediment and rock and flat rock outcrop) likely is due to the relatively narrow and intermittent nature of transition zones from sediment to rock and also the size of the buffer. 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 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 (89 percent for Class I, 74 percent for Class II, 99 percent for Class III, and 100 percent for Class IV).

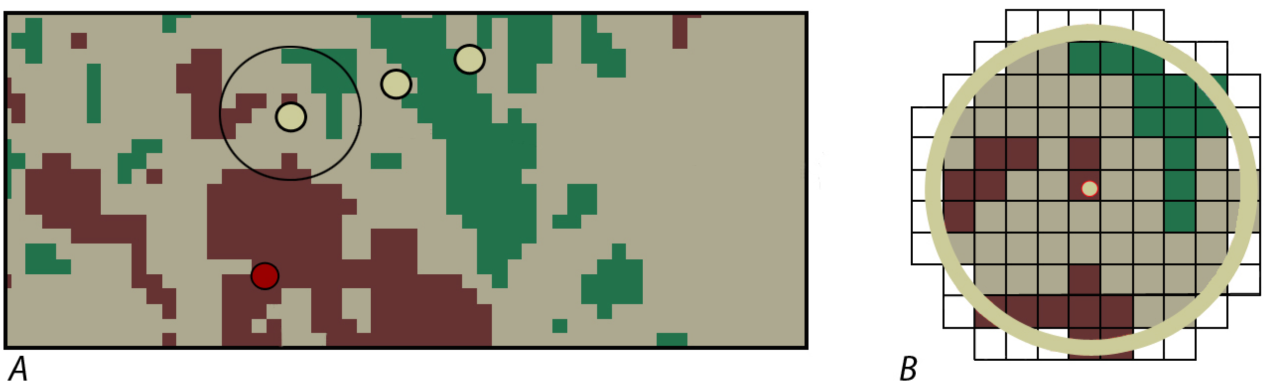

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

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

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

[Accuracy assessments are based on video observations]

Class	Number of observations	% majority	% presence/absence
I—Fine- to medium-grained smooth sediment	132	72.2	89.4
II—Mixed smooth sediment and rock	39	31.0	74.4
III—Rock and boulder, rugose	166	83.6	98.8
IV—Medium- to coarse-grained sediment (in scour depressions)	42	97.6	100.0

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

By Nadine E. Golden and Guy R. Cochrane

To validate the interpretations of sonar data in order to turn it into geologically and biologically useful information, the U.S. Geological Survey (USGS) towed a camera sled (fig. 5–1) over specific locations throughout the Offshore of Pigeon Point map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred on two separate cruises in 2007 and 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 8 trackline kilometers of video and 1,410 still photographs, in addition to 390 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

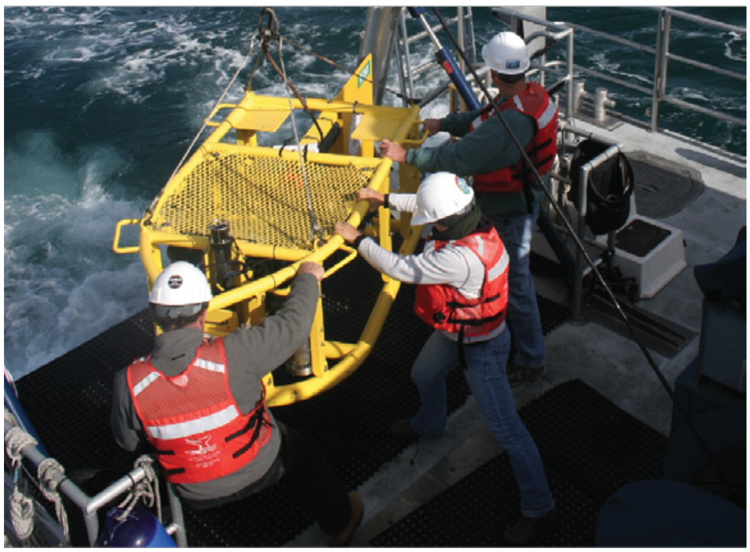

Figure 5–1. Photograph of camera sled used in USGS 2007 ground-truth survey.

During the ground-truth-survey cruises, the USGS camera sled housed two standard-definition (640×480 pixel resolution) video cameras (one forward looking, and one downward looking), as well as a high-definition (1,080×1,920 pixel resolution) video camera and an 8-megapixel digital still camera. During these cruises, in addition to recording the seafloor characteristics, a digital still photograph was captured once every 30 seconds.

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

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

Sheet 6 contains a smaller, simplified (depth-zone symbology has been removed) version of the seafloor-character map on sheet 5. On this simplified map, the camera-sled tracklines used to ground-truth-survey the sonar data are shown by aligned colored dots, each dot representing the location of a recorded observation. A combination of abiotic attributes (primary- and secondary-substrate compositions), as well as vertical variability, were used to derive the different classes represented on the seafloor-character map (sheet 5); on the simplified map, the derived classes are represented by colored dots. Also on this map are locations of the detailed views of seafloor character, shown by boxes (Boxes A through 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 surface in the Offshore of Pigeon Point map area predominantly consists of high-relief rocky habitat in the nearshore and also out to water depths of 45 m; sand habitat dominates in deeper waters (see also, sheets 5, 7, 9).

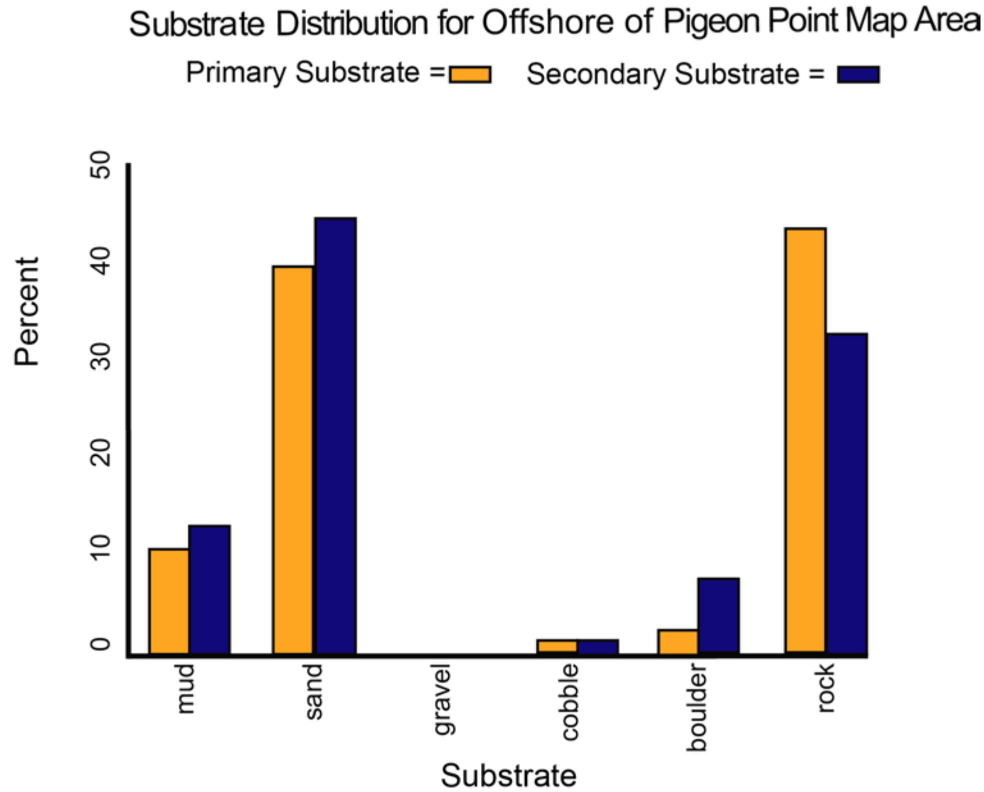

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Pigeon Point map area.

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

By H. Gary Greene and Charles A. Endris

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

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

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

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

Classifying Potential Marine Benthic Habitats

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

The four categories and their attribute codes that are used on the Offshore of Pigeon Point 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)

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

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

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

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

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

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

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

Examples of Attribute Coding

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

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

Map Area Habitats

The Offshore of Pigeon Point map area includes the nearshore and inner shelf areas from just north of Pigeon Point to Point Año Nuevo. Delineated on the map are 9 potential marine benthic habitat types, all of which are located on the continental shelf (“Shelf” megahabitat). These include soft, unconsolidated sediment (5 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 (1 habitat type) such as soft sand and gravels that overlie hard consolidated sedimentary bedrock and gravel pavement; and hard substrate (3 habitat types) such as deformed and differentially eroded bedrock, as well as pinnacles and boulders.

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, and, thus, habitats are highly dynamic, with sediment transport primarily to the southeast. An extensive exposure of deformed and differentially eroded bedrock is located in the southeast part of the map area, offshore of Point Año Nuevo, and it potentially provides good habitat for rockfish (*Sebastes* spp.).

Of the 134.34 km^2 mapped on the continental shelf in the Offshore of Pigeon Point map area, soft, unconsolidated sediment is the dominant habitat type, covering 108.36 km^2 (80.7 percent). Hard rock covers 22.78 km^2 (17.0 percent), and 3.19 km^2 (2.4 percent) is mixed hard-soft substrate.

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

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

The seismic-reflection profiles presented on sheet 8 provide a third dimension—depth beneath the seafloor—to complement the surficial seafloor-mapping data already presented (sheets 1 through 7) for the Offshore of Pigeon Point map area. These data, which are collected at several resolutions, extend to varying depths in the subsurface, depending on the purpose and mode of data acquisition. The seismic-reflection profiles (sheet 8) provide information on sediment character, distribution, and thickness, as well as potential geologic hazards, including active faults, areas prone to strong ground motion, and tsunamigenic slope failures. The information on faults provides essential input to national and state earthquake-hazard maps and assessments (see, for example, Petersen and others, 2014).

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

Data Acquisition

Most profiles displayed on sheet 8 (figs. 1, 2, 3, 5, 6, 8, 9) were collected in 2009 and 2010 on U.S. Geological Survey (USGS) cruises S–N1–09–MB and S–15–10–NC, respectively. The single-channel seismic-reflection data were acquired using a SIG 2Mille minisparker that used a 500-J high-voltage electrical discharge fired 2 times per second, which, at normal survey speeds of 4 to 4.5 nautical miles/hour, gives a data trace every 1.0 to 1.5 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 4 and 7 on sheet 8 show migrated, deep-penetration, multichannel seismic-reflection profiles collected in 1976 by WesternGeco on cruise W–14–76–SF. 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 (U.S. Geological Survey, 2009). These data were acquired using a large-volume air-gun source that has a frequency range of 3 to 40 Hz and recorded with a multichannel hydrophone streamer about 2 km long. Shot spacing was about 30 m. These data can resolve geologic features that are 20 to 30 m thick, down to subbottom depths of as much as 4 km.

Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Pigeon Point map area, providing an image of the subsurface geology. The offshore part of the map area is characterized by relatively flat (less than 1°) inner shelf and midshelf areas, reaching water depths of about 70 m at the limit of

California’s State Waters. Most of the shelf north of Point Año Nuevo is underlain by unconsolidated sandy and muddy sediment. Bedrock forms moderate-relief outcrops that locally extend from the shoreline to water depths of about 30 m, except offshore of Point Año Nuevo, where seafloor bedrock is exposed out to water depths of greater than 40 m (see sheets 1, 2, 10). The seismic-reflection profiles provide the data for interpreting subbottom stratigraphy, sediment thickness, and geologic structure (see sheets 9, 10).

On seismic-reflection profiles, the Upper Cretaceous Pigeon Point Formation is essentially nonreflective (see figs. 1, 2, 5 on sheet 8). The overlying Tertiary strata, which are moderately to highly deformed, are generally characterized by continuous, parallel to subparallel, variable-amplitude, high-frequency reflections (terminology from Mitchum and others, 1977). West of the San Gregorio Fault Zone, the onshore Tertiary section (Brabb and others, 1998; Clark and others, 1999) includes rocks of the Oligocene and Miocene unnamed sedimentary and volcanic rocks unit, the middle and upper Miocene Monterey Formation, and the upper Miocene and Pliocene Purisima Formation (Powell and others, 2007). Notably, the upper Miocene Santa Cruz Mudstone is absent in the onshore section west of the San Gregorio Fault Zone; however, the Santa Cruz Mudstone is present in offshore wells within the Outer Santa Cruz Basin (Heck and others, 1990), and it may also be present in the subsurface to the south, within the offshore part of the Offshore of Pigeon Point map area.

Throughout the map area, the contact between the Tertiary bedrock and the overlying upper Quaternary sediments is an angular unconformity that commonly is marked by minor channeling, an eastward onlap onto reflection-free bedrock, and an upward change to lower amplitude, more diffuse reflections. Two upper Quaternary units are recognized in the broader mapping region (see sheet 9, Maps C, D). Although it is not present in this map area, the lower unit notably includes low-amplitude, low-angle (1° to 3°), offshore-dipping clinoforms (Catuneanu, 2006). The upper unit, which is present in the map area, typically is characterized by low-amplitude, continuous to moderately continuous, diffuse, subparallel reflections, and it has a maximum thickness of about 22 m (see figs. 1, 2, 3, 5, 6, 8, 9 on sheet 8).

Eustasy was an important control on late Quaternary deposition. Surficial and shallow sediments were deposited in the last about 21,000 years during the major sea-level lowstand associated with the Last Glacial Maximum (LGM) and its subsequent sea-level rise (Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006). Global sea level was about 125 m lower than present during the LGM, at which time the Offshore of Pigeon Point map area was emergent and the shoreline was about 12 km west of its present location. Sea-level fall prior to the LGM led to the westward migration of the shoreline and wave-cut platform, as well as the subaerial exposure and subsequent incision of the continental shelf. 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). Post-LGM sea-level rise led to a broadening of the continental shelf, the progressive eastward migration of the shoreline and wave-cut platform, and the associated transgressive erosion and deposition.

Our preferred hypothesis is that the lower of the two upper Quaternary sedimentary units (not present in this map area) represents a progradational delta and (or) shoreface that formed between about 30,000 and 21,000 years ago during the pre-LGM sea-level drop of marine-isotope stage 2 (Waelbroeck and others, 2002). The overlying upper unit (blue shading in profiles on sheet 8) represents shelf deposits that formed during the post-LGM sea-level rise of the last about 21,000 years (Stanford and others, 2011). In this interpretation, the surface at the base of the upper unit throughout the map area is a transgressive surface of erosion that formed as the shoreface migrated landward. Because the two upper Quaternary units each consist of unconsolidated upper Quaternary sediments and together overlie the prominent angular unconformity with bedrock, we have combined their thicknesses on the regional thickness maps (Maps B, D) on sheet 9

Geologic Structure and Recent Deformation

Faults in the offshore part of the Offshore of Pigeon Point map area are identified in seismic-reflection profiles on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as reflection presence, amplitude, frequency, geometry, continuity, and vertical sequence. The Offshore of Pigeon Point map area encompasses a part of the continental shelf that lies between the Ascension Fault and the San Gregorio Fault Zone, along the northeastern margin of the Outer Santa Cruz Basin and the southwest limb of the Pigeon Point high (McCulloch, 1987) (figs. 7, 10 on sheet 8). The Ascension Fault is a high-angle reverse fault that bounds an area of uplift within the Outer Santa Cruz Basin (Nagel and others, 1986; Wagner and others, 2002; Dickinson and others, 2005). This uplifted area on the continental shelf area is characterized by a number of steeply dipping, predominantly northwest-striking, unnamed faults that are truncated by the San Gregorio Fault Zone. These unnamed faults show a vertical separation of reflections and commonly juxtapose reflection panels that have differing seismic parameters, suggesting a combination of reverse and strike-slip faulting. This faulting is associated with a complex pattern of folding, particularly within the Monterey Formation offshore of Point Año Nuevo (see figs. 6, 8 on sheet 8; see also, sheet 10). Rates of Pleistocene-age vertical uplift onshore, west of the San Gregorio Fault Zone, range from 0.31 to 0.35 m/ka (Clark and others, 1999), and cumulative lateral slip on the San Gregorio Fault Zone is thought to range from 4 to 10 mm/yr in this area (Weber and others, 1995).

Map E on sheet 9 shows the regional pattern of major faults and recorded earthquakes. Fault locations, which have been simplified, are compiled from our mapping within California's State Waters (see sheet 10), from Wagner and others (2002), and from the U.S. Geological Survey's Quaternary fault and fold database (U.S. Geological Survey and California Geological Survey, 2010). Earthquake epicenters are from the Northern California Earthquake Data Center (2014), which is maintained by the U.S. Geological Survey and the University of California, Berkeley, Seismological Laboratory; all events that have inferred or measured magnitudes of 2.0 and greater for the time period 1967 through April 2014 are shown. The 1989 Loma Prieta earthquake (M6.9, 10/17/1989), on the San Andreas Fault Zone in the Santa Cruz Mountains (Spudich, 1996), is the most significant event in the region. In the Offshore of Pigeon Point map area, a substantial amount of seismicity is broadly distributed between the San Gregorio Fault Zone and the Ascension Fault—the largest recorded earthquake (M3.6) having occurred on 6/28/1991.

Thickness and Depth to Base of Uppermost Pleistocene and Holocene Deposits

Maps on sheet 9 show the interpreted thickness and the depth to base of uppermost Pleistocene and Holocene deposits, both for the Offshore of Pigeon Point 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). To make these maps, water bottom and depth to base of the uppermost Pleistocene and Holocene sediment layer were mapped from seismic-reflection profiles (see fig. 1 on sheet 9; see also, sheet 8). The difference between the two horizons was exported for every shot point as XY coordinates (UTM zone 10) and two-way travel time (TWT). The thickness of the uppermost Pleistocene and Holocene unit (Maps B, D) was determined by applying a sound velocity of 1,600 m/sec to the TWT. The thickness points were interpolated to a preliminary continuous surface, overlaid with zero-thickness bedrock outcrops (see sheet 10), and contoured, following the methodology of Wong and others (2012).

Several factors required manual editing of the preliminary sediment-thickness maps to make the final product. The Monterey Bay, San Andreas, and San Gregorio Fault Zones disrupt the sediment sequence in the region (Maps D, E on sheet 9). The thickness data points also are dense along tracklines (about 1 m apart) and sparse between tracklines (1,000 to 1,250 m apart), resulting in minor contouring artifacts. To incorporate the effects of the faults, to remove irregularities from interpolation, and to reflect other geologic information and complexity, the resulting interpolated contours were modified. Contour modifications and regridding were repeated several times to produce the final sediment-thickness maps (Maps B, D). Information for the depth to base of the uppermost Pleistocene and Holocene unit (Maps A, C) was generated by adding the thickness data to water depths determined by multibeam bathymetry (see sheet 1).

The thickness of the post-LGM unit in the Offshore of Pigeon Point map area ranges from 0 to 22 m (Map B on sheet 9), and the depth to the base of this unit ranges from less than 10 to 75 m (Map A). Mean sediment thickness for the map area is 6.0 m, and the total sediment volume is 765×10^6 m^3 (table 7–1). The thickest sediment in the map area is found in the northwest corner of the map area (Map B; see also, fig. 1 on sheet 9), coincident with a decrease in slope on the bedrock unconformity (Maps A, C). Sediment thickness diminishes to the southeast, and the sediment cover offshore of Point Año Nuevo is either thin or nonexistent (Maps B, D). The extensive bedrock outcrop in this area coincides with an area of transpression between the Ascension Fault and the San Gregorio Fault Zone. The relative lack of offshore sediment probably is a result of both low sediment supply and its ongoing exposure to erosive wave energy.

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. Note that 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 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 that has sediment as thick as 32 m, much of which was deposited in a pre-LGM prograding delta and (or) shoreface complex and was preserved above a decrease in slope on the underlying unconformity; and (c) a midshelf to outer shelf zone in which sediment generally becomes progressively thinner in the offshore direction.

(3) The Davenport shelf domain extends from the northern limit of Monterey Bay northward to the southern margin of the Waddell Creek depocenter. 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 attributable 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 Offshore of Pigeon Point map area.

Regional sediment-thickness domains in Pigeon Point to southern Monterey Bay region			
	Area (km^2)	Mean sediment thickness (m)	Sediment volume (10^6 m^3)
Entire Pigeon Point to southern Monterey Bay region	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 Offshore of Pigeon Point map area			
Entire Offshore of Pigeon Point map area	130	5.9	765
Waddell Creek delta	7	4.7	34
Año Nuevo shelf	54	2.5	134
Pigeon Point shelf	68	8.8	598

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

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

Geologic and Geomorphic Summary

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

Onshore geology was compiled from Weber and Lajoie (1980), Smith (1981), California Geological Survey (1982a,b), Brabb (1997), Brabb and others (1998), Clark and others (1999), and Graymer and others (2006); unit ages, which are from these sources, reflect local stratigraphic relations. In addition, some units were modified by C.W. Davenport on the basis of analysis of 2012 lidar imagery.

The offshore part of the map area, which includes the seafloor off the prominent headland of Point Año Nuevo, extends from the shoreline to water depths of about 70 m. The map area is characterized largely by a relatively flat (less than 1°) bedrock platform that is overlain by a variably thick (as much as 22 m) veneer of upper Quaternary sediment (see Map B on sheet 9). Sea level has risen about 120 to 130 m during the last about 21,000 years (see, for example, Stanford and others, 2011), leading to a broadening of the continental shelf, the progressive eastward migration of the shoreline and wave-cut platform, and the associated transgressive erosion and deposition of sediment (see, for example, Catuneanu, 2006). Land-derived sediment was carried into this setting and then subjected to Pacific Ocean wave energy and strong currents before deposition or offshore transport. Shelf morphology and geology are result from local faulting, folding, uplift, and subsidence.

Most of the Offshore of Pigeon Point map area encompasses a part of the continental shelf that lies between the Ascension Fault and the San Gregorio Fault Zone, along the northeastern margin of the Outer Santa Cruz Basin and the southwest limb of the Pigeon Point high (McCulloch, 1987) (fig. 1 on sheet 10). The northwest-striking San Gregorio Fault Zone (Weber and others, 1995; Dickinson and others, 2005), an important right-lateral strike-slip fault within the San Andreas Fault System, cuts across land through the northeast corner of the map area before moving offshore at Point Año Nuevo. In the map area, the San Gregorio Fault system forms a distributed shear zone about 1 to 4 km wide that includes two main diverging fault strands (fig. 1 on sheet 10). The west strand (known as the Frijoles Fault), which comes onshore approximately 0.5 km east of Año Nuevo Creek, coincides with a topographic trough to the north (Clark and others, 1999). The east strand (known as the Coastways Fault) forms a prominent scarp offshore, where rocks of the Santa Cruz Mudstone east of the fault are juxtaposed with those of the Purisima Formation west of the fault. Paleoseismic data presented by Simpson and others (1997) suggest a post–late Pleistocene slip rate of 3.5 to 4.5 mm/yr for the onshore part of the east strand. This estimated rate represents a minimum for the San Gregorio Fault system because fault strands to the west, including the Frijoles Fault, are also active. Cumulative lateral slip on this fault zone is thought to range from 4 to 10 mm/yr in this area (Weber and others, 1995).

The northwest-striking Ascension Fault (fig. 1 on sheet 10) is a high-angle reverse fault (Nagel and others, 1986; Wagner and others, 2002; Dickinson and others, 2005) that is considered to be active (U.S. Geological Survey and California Geological Survey, 2010) and is characterized by a series of northeast-dipping thrust faults sub-parallel to the San Gregorio Fault Zone. The offshore area between the Ascension Fault and the San Gregorio Fault Zone is characterized by a number of steeply dipping, predominantly northwest-striking, unnamed faults and also northwest-trending folds.

The Upper Cretaceous Pigeon Point Formation (unit Kpp), which represents the oldest bedrock unit exposed in the offshore part of the map area, crops out on the seafloor in shallow water (less than 30 meters deep) north of Point Año Nuevo and west of the San Gregorio Fault Zone. These basement rocks are unconformably overlain by Tertiary marine sedimentary rocks, which include the middle and upper Miocene Monterey Formation (unit Tm), the upper Miocene Santa Cruz Mudstone (unit Tsc), and the upper Miocene and Pliocene Purisima Formation (unit Tp; age from Powell and others, 2007). The undivided Oligocene to upper Pliocene sedimentary rocks unit (Tu) is mapped in the offshore where assignment to a particular formation is uncertain; this undivided unit may also include a relatively thin (85 m thick) section of volcanic rocks, which has been mapped onshore along the coast at Point Año Nuevo as the unnamed sedimentary and volcanic rocks unit (Tuv).

The Santa Cruz Mudstone (Tsc) is mapped east of the Coastways Fault (east strand of the San Gregorio Fault Zone) both in the nearshore and onshore in the seacliff. However, the Santa Cruz Mudstone is not present within the Tertiary section onshore west of the Coastways Fault, where the Purisima Formation unconformably overlies either the Pigeon Point Formation or the Monterey Formation. The Purisima Formation is exposed on the seafloor in Año Nuevo Bay between the Coastways and Frijoles Faults. Seafloor exposures of the Purisima Formation and the underlying Monterey Formation are difficult to distinguish west of the Frijoles Fault in multibeam bathymetry imagery (see sheets 1, 2); however, the faulted unconformity between the Purisima and Monterey Formations is clearly visible in seismic-reflection profiles southeast of Point Año Nuevo (see fig. 9 on sheet 8).

Modern nearshore sediments are mostly sand (unit Qms) and a mix of sand, gravel, and cobbles (units Qmsc and Qmsd). Unit Qms notably is present, in addition to on the shelf, in well-defined channels that cut through nearshore bedrock exposures north of Pigeon Point. These distinct channels, which extend to water depths of 20 to 30 m, were formed by subaerial erosion during sea-level lowstands (Anima and others, 2002). The coarser grained sands and gravels (units Qmsc and Qmsd) are recognized primarily on the basis of bathymetry and high backscatter (see sheets 1, 2, 3). Unit Qmsc mainly is found adjacent to bedrock, in water depths of less than 40 m.

Unit Qmsd typically is mapped as erosional lags in scour depressions (see, for example, Cacchione and others, 1984) that are bounded by relatively sharp or, less commonly, diffuse contacts with the horizontal sand sheets of unit Qms. These depressions typically are a few tens of centimeters deep and range in size from a few tens of square meters to more than 1 km^2. Such scour depressions are common along this stretch of the California coast (see, for example, Cacchione and others, 1984; Hallenbeck and others, 2012; Davis and others, 2013), where offshore sandy sediment can be relatively thin (and, thus, is unable to fill the depressions) owing to low sediment supply from rivers and also to significant erosion and offshore transport of sediment during large northwest winter swells. Such features have been referred to as “rippled scour depressions” (see, for example, Cacchione and others, 1984) or “sorted bedforms” (see, for example, Murray and Thieler, 2004; Goff and others, 2005; Trembanis and Hume, 2011). Although the general areas in which both unit Qmsd scour depressions and surrounding Qms sand sheets are found are not likely to change substantially, the boundaries of the unit(s) likely are ephemeral, changing seasonally and during significant storm events.

A transition to finer grained marine sediments (unit Qmsf) is seen offshore of Pigeon Point and southwest of Point Año Nuevo, at water depths of 50 to 60 m. Unit Qmsf, which commonly is extensively bioturbated, primarily consists of mud and muddy sand. These fine-grained shelf sediments are derived from local coastal watersheds, bluff erosion, and the northward advection of sediment from fluvial sources within, and north of, Monterey Bay (Edwards, 2002).

In areas where shelf sediments form thin (less than 2.5 m) veneers over low-relief rocks of the upper Miocene and Pliocene Purisima Formation, composite unit Qms/Tp is mapped. This composite unit is recognized on the basis of the combination of flat relief, continuity with moderate- to high-relief bedrock outcrops, high-resolution seismic-reflection data (see sheet 8), and moderate to high backscatter (see sheet 3). Overlying sediment is interpreted as an ephemeral and dynamic sediment layer that may or may not be continuously present, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term climate cycles. Storlazzi and others (2011) described the seasonal burial and exhumation of submerged bedrock in a similar high-energy setting in northern Monterey Bay, just south of the map area.

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

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine sedimentary units			
Qms	79,718,281	79.7	57.7
Qmsc	1,045,303	1.0	0.8
Qmsd	2,087,107	2.1	1.5
Qmsf	23,740,499	23.7	17.2
Total, sedimentary units	106,591,191	106.5	77.2
Marine bedrock and (or) shallow bedrock units			
Qms/Tp	87,656	0.1	0.1
Tm	15,103,036	15.1	10.9
Tp	4,102,837	4.1	3.0
Tsc	401,293	0.4	0.3
Tu	318,979	0.3	0.2
Kpp	11,494,770	11.5	8.3
Total, bedrock units	31,508,571	31.5	22.8
Total, Offshore of Pigeon Point map area	138,099,762	138.1	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) Quaternary deposits, composite units are mapped. These composite units, which are shown with gray stipple pattern on older unit, are designated by composite label indicating both overlying sediment cover and lower (older) unit, separated by slash (for example, Qms/Tp indicates that thin sheet of Qms overlies Tp)]

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

Qmsd **Marine shelf scour depressions (late Holocene)—**Inferred to be coarse sand and possibly gravel; consists of irregular, arcuate scour depressions that range from solitary features that occupy a few hundred square meters to fields of interconnected depressions covering tens of thousands of square meters. Found as single depressions or in fields of depressions interspersed with elevated shelf sediments (units Qms and Qmsf). Depressions are typically are 15 to 50 cm deep and 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

Qmsf **Fine-grained marine shelf deposits (late Holocene)—**Predominantly mud, very fine sand, and silt; found at water depths greater than about 60 m

Qmsc **Coarse-grained marine nearshore and shelf deposits (late Holocene)—**Predominantly coarse sand and gravel

Tp **Purisima Formation (Pliocene and late Miocene)—**Predominantly gray and greenish-gray to buff, fine-grained marine sandstone, siltstone, and mudstone; also includes some porcelaneous shale and mudstone, chert, silty mudstone, and volcanic ash. Stippled areas (composite unit Qms/Tp) indicate where thin sheets of Qms overlie unit. Age is based on biostratigraphic and geochronologic data summarized by Powell and others (2007)

Tu **Sedimentary and volcanic rocks, undivided (late Pliocene to Oligocene)—**Consists of rocks of the Purisima Formation (Tp), the Monterey Formation (Tm), and the unnamed sedimentary and volcanic rocks unit (Tuv)

Tsc **Santa Cruz Mudstone (late Miocene)—**Thin- to thick-bedded, marine, siliceous and nonsiliceous mudstone and siltstone; includes minor amounts of sandstone

Tm **Monterey Formation (late and middle Miocene)—**Marine, thin-bedded, porcelaneous shale and chert, porcelaneous mudstone, diatomite, claystone; includes siltstone and sandstone near base. Visible in multibeam-bathymetry imagery as highly fractured bedrock exposed on seafloor offshore of Point Año Nuevo

Kpp **Pigeon Point Formation (Late Cretaceous)—**Sandstone and conglomerate, interbedded with siltstone and mudstone. Exposed on seafloor in nearshore (less than 30 m deep) offshore of Pigeon Point and Franklin Point

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units compiled from Weber and Lajoie (1980), Smith (1981), California Geological Survey (1982a,b), Brabb (1997), Brabb and others (1998), Clark and others (1999), and Graymer and others (2006); unit ages, which are from these sources, reflect local stratigraphic relations. In addition, some units modified by C.W. Davenport on basis of analysis of 2012 lidar imagery]

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

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

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

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

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

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

Qyf **Alluvial fan deposits (Holocene)**—Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains; may include sand, gravel, silt, and clay; deposits identified primarily by fan morphology and topographic expression

Qb **Basin deposits (Holocene)**—Fine-grained sediment that accumulates from standing or slow-moving water in topographic basins and, locally, between adjacent alluvial fans

Qt **Stream-terrace deposits (Holocene)**—Relatively smooth, undissected, relatively low-lying terraces adjacent to active stream channels

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

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

Qot **Stream-terrace deposits (Holocene and late Pleistocene)**—Sand, gravel, silt, and minor clay of uncertain age; underlies relatively flat platforms adjacent to stream channels

Qya **Alluvial deposits, undivided (late Pleistocene)**—Mapped on gently sloping to level terrace surfaces, where late Pleistocene age is indicated by depth of stream incision; also mapped where separate units could not be delineated at map scale

Qof2 **Alluvial fan deposits (late Pleistocene)**—Mapped where late Pleistocene age is indicated by greater degree of dissection, than is present on Holocene fans, or where geomorphic feature lies at higher elevation, than that of Holocene fans

Qmt **Marine-terrace deposits, undivided (Pleistocene)**—Sand and gravel; deposited on uplifted marine-abrasion platforms along coast; queried where uncertain. Locally includes dune sand where too small or numerous to show at map scale

Qoa **Older alluvial deposits, undivided (Pleistocene)**—Moderately to deeply dissected alluvial deposits; commonly consists of gently rolling hills that have little or no original planar surface preserved

Qof1 **Alluvial fan deposits (Pleistocene)**—Moderately to deeply dissected alluvial fan deposits; mapped where some original fan surface morphology is preserved

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

Tsc **Santa Cruz Mudstone (late Miocene)—**Siliceous mudstone, interbedded with nonsiliceous mudstone, siltstone, and minor sandstone

Tsm **Santa Margarita Sandstone (late Miocene)—**Friable, very fine- to very coarse-grained, arkosic sandstone; quartz- and feldspar-pebble conglomerate crops out locally at base of section

Tm **Monterey Formation (late and middle Miocene)—**Porcelaneous shale and chert, porcelaneous mudstone, calcareous claystone; includes small amounts of siltstone and sandstone near base

Tuv **Unnamed sedimentary and volcanic rocks (Miocene and Oligocene)—**Dark-gray, hard mudstone

Tb **Butano Sandstone (middle and early Eocene)—**Very fine- to very coarse-grained, arkosic sandstone, interbedded with mudstone and shale; conglomerate is present locally in lower part of section

Kpp **Pigeon Point Formation (Late Cretaceous)—**Sandstone and conglomerate, interbedded with siltstone and mudstone

KJv **Unnamed volcanic rocks (Cretaceous or Jurassic)—**Finely crystalline, felsic volcanic rocks that contain quartz and albite phenocrysts

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