California State Waters Map Series—Offshore of San Gregorio, California

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

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

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

Preface

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

The CSMP approach is to create highly detailed seafloor maps through collection, integration, interpretation, and visualization of swath sonar 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 (to about 100 m) subsurface geology. It is emphasized that the more interpretive habitat and geology maps rely on the integration of multiple, new high-resolution datasets and that mapping at small scales would not be possible without such data.

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

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

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raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed May 31, 2013).

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

Chapter 1. Introduction

By Guy R. Cochrane

Regional Setting

The map area offshore of San Gregorio, California, which is referred to herein as the “Offshore of San Gregorio” map area (figs. 1–1, 1–2), is located in northern California, on the Pacific coast of the San Francisco Peninsula about 50 kilometers south of the Golden Gate. The nearest significant onshore cultural centers are San Gregorio and Pescadero, both unincorporated communities with populations well under 1,000 (fig. 1–1). Both communities are situated inland of state beaches that share their names. No harbor facilities are within the Offshore of San Gregorio map area. The hilly coastal area is virtually undeveloped grazing land for sheep and cattle.

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

The coastal geomorphology is controlled by late Pleistocene and Holocene slip in the San Gregorio Fault system (Dickinson and others, 2005). A westward bend in the San Andreas Fault Zone, southeast of the map area, coupled with right-lateral movement along the San Gregorio Fault system (Weber, 1990) have caused regional folding and uplift. The coastal area consists of high coastal bluffs and vertical sea cliffs (Griggs and others, 2005). Coastal promontories in the northern and southern parts of the map area are the result of right-lateral motion on strands of the San Gregorio Fault system (see sheet 9). In the south, headlands near Pescadero Point have been uplifted by motion along the west strand of the San Gregorio Fault (also called the Frijoles Fault), which separates rocks of the Pigeon Point Formation south of the fault from rocks of the Purisima Formation north of the fault. The regional uplift in this map area has caused relatively shallow water depths within California’s State Waters and, thus, little accommodation space for sediment accumulation. Sediment is observed offshore in the central part of the map area, in the shelter of the headlands north of the east strand of the San Gregorio Fault (also called the Coastways Fault) around Miramontes Point (about 5 km north of the map area) and also on the outer half of the California’s State Waters shelf in the south where depths exceed 40 m (see sheet 9). Sediment in the outer shelf of California’s State Waters is rippled, indicating some mobility (see sheet 6).

Coastal sediment transport in the Offshore of San Gregorio map area is characterized by north-to-south littoral transport of sediment derived mainly from intermittent streams and local coastal erosion (Hapke and others, 2006). Offshore beyond California’s State Waters, unnamed submarine canyons that incise the slope have been disconnected from coastal streams by the rising sea level, which has risen about 125 m since the lowstand associated with the Last Glacial Maximum, about 20,000 to 18,000 years ago (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Lambeck and others, 2002). In the map area, no major submarine canyons extend from the shelf break up into the nearshore to receive littoral drift. Griggs and others (2005) categorized erosion of the coastline in most of the map area as “stable low risk,” the exception being an area near Pescadero Creek where wave erosion has required the placement of riprap revetments to protect Highway 1. In addition, severe beach erosion occurred during winter storms in 1982–83 north of the mouth of Tunitas Creek.

The Offshore of San Gregorio map area lies within 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, an eastern limb of the North Pacific subtropical gyre that flows from Oregon to Baja California. At its midpoint off central California, the California Current transports subarctic surface (0–500 m deep) waters southward, about 150 to 1,300 km from shore (Lynn and Simpson, 1987; Collins and others, 2000). Seasonal northwesterly winds (Inman and Jenkins, 1999) that are, in part, responsible for the California Current, generate coastal upwelling. The south end of the Oregonian province is at Point Conception (about 350 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).

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

Publication Summary

This publication about the Offshore of San Gregorio 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; this “ground-truth” surveying data is summarized on sheet 6. Sheet 5 is a “seafloor character” map, which classifies the seafloor on the basis of depth, slope, rugosity (ruggedness), and backscatter intensity and which is further informed by the ground-truth-survey imagery. Sheet 7 is a map of “potential habitats,” which are delineated on the basis of substrate type, geomorphology, seafloor process, or other attributes that may provide a habitat for a specific species or assemblage of organisms. Sheet 8 compiles representative seismic-reflection profiles from the map area, providing information on the subsurface stratigraphy and structure of the map area. Sheet 9 shows the distribution and thickness of young sediment (deposited over the last about 21,000 years, during the most recent sea-level rise) in both the map area and the larger Bolinas to Pescadero region, interpreted on the basis of the seismic-reflection data. Sheet 10 is a geologic map that merges onshore geologic mapping (compiled from existing maps by the California Geological Survey) and new offshore geologic mapping that is based on integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

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

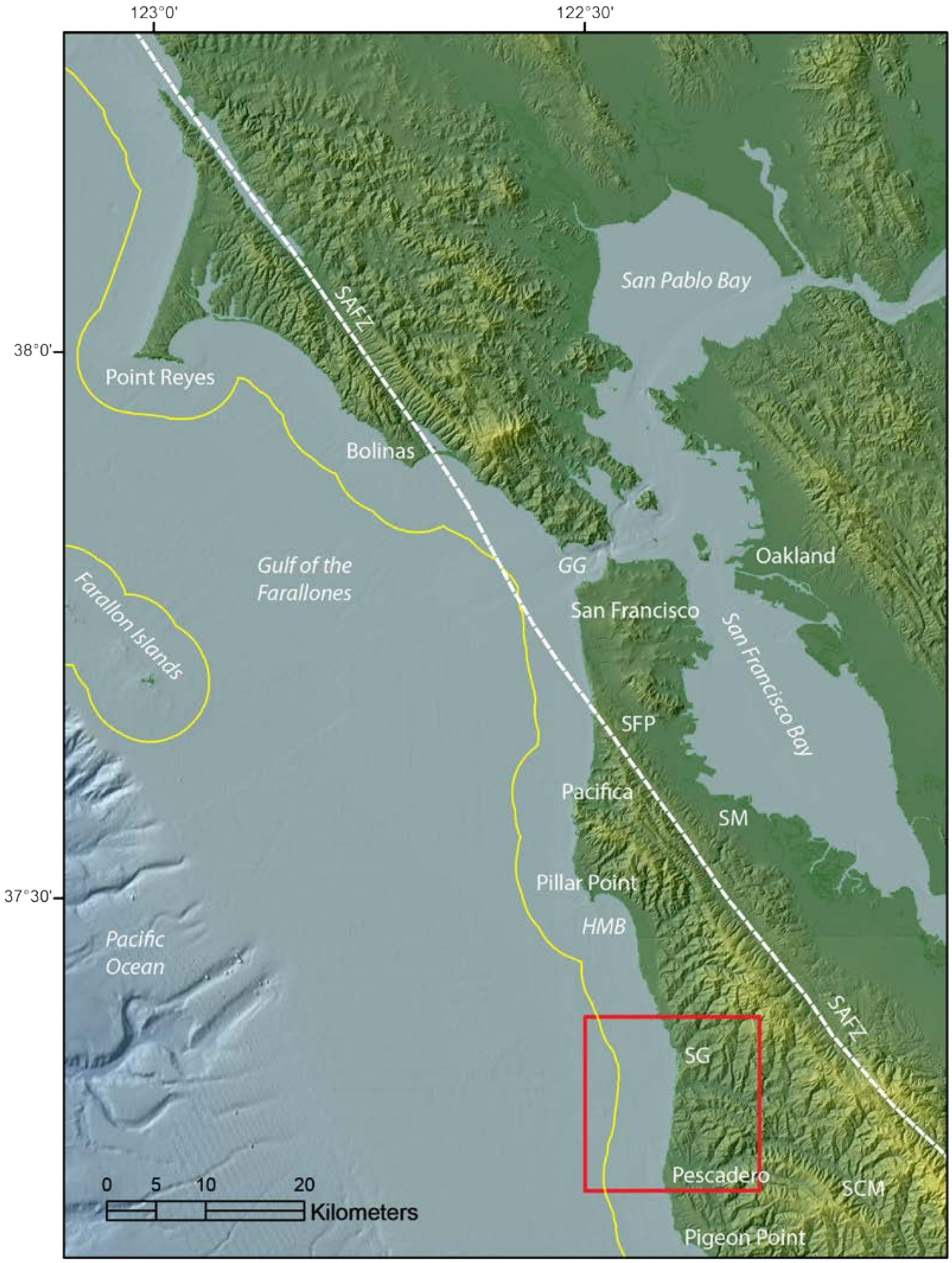

Figure 1–1. Physiography of Bolinas to Pescadero region and its environs. Box shows Offshore of San Gregorio map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Other abbreviations: GG, Golden Gate; HMB, Half Moon Bay; PP, Pillar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

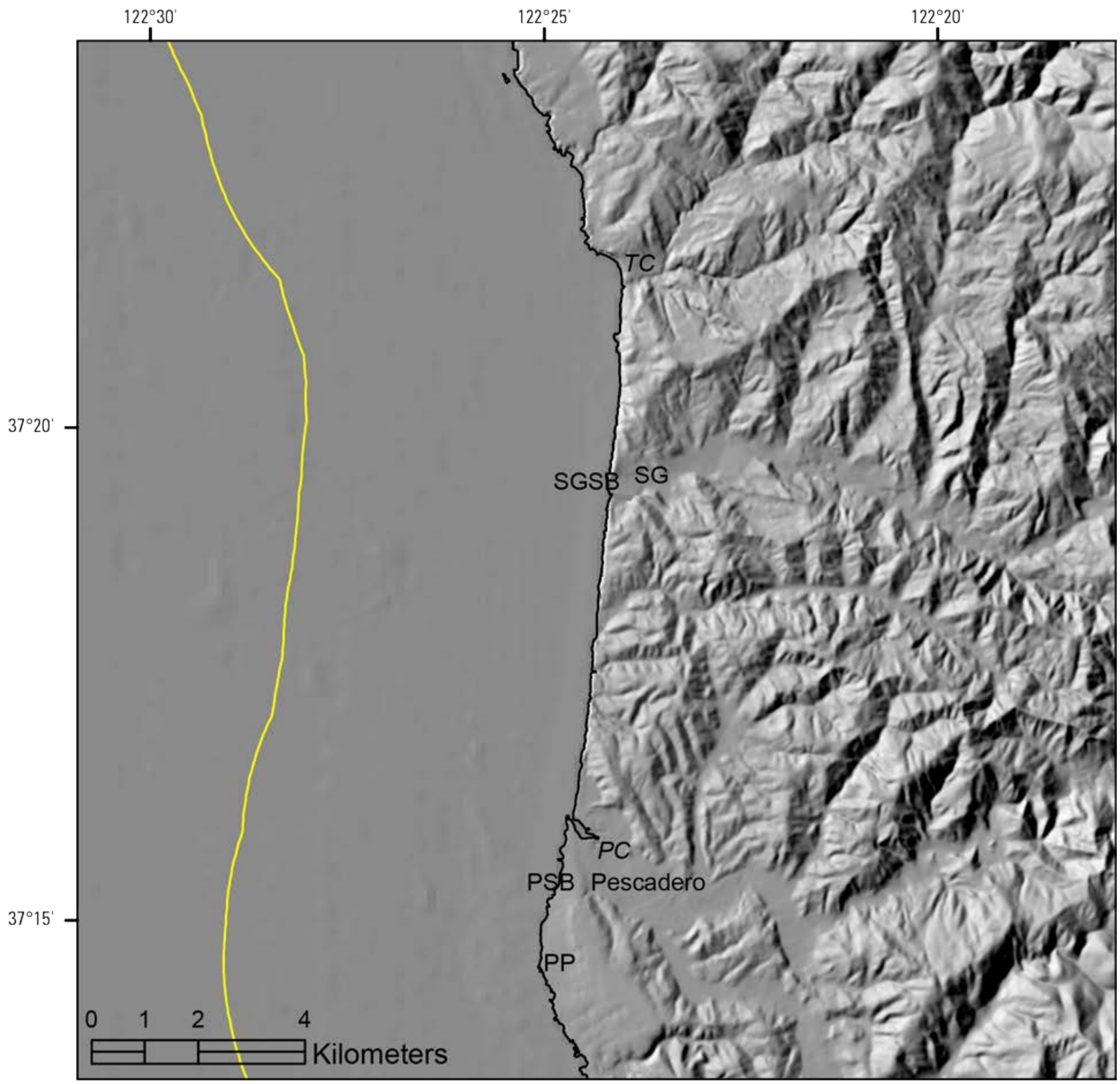

Figure 1–2. Coastal geography of Offshore of San Gregorio map area. Yellow line shows limit of California's State Waters. Abbreviations: PC, Pescadero Creek; PP, Pescadero Point; PSB, Pescadero State Beach; SG, San Gregorio; SGSB, San Gregorio State Beach; TC, Tunitas Creek.

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

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

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of San Gregorio map area in northern California were generated from bathymetry and backscatter data collected by Fugro Pelagos and by California State University, Monterey Bay (CSUMB) (fig. 1 on sheets 1, 2, 3). The nearshore area was mapped by CSUMB in 2007; the areas further offshore, by Fugro Pelagos in 2006 and 2007. Both used a combination of 400-kHz Reson 7125 and 244-kHz Reson 8101 multibeam echosounders. These mapping missions combined to collect both bathymetry (sheets 1, 2) and acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 3-nautical-mile limit of California's State Waters.

During all the mapping missions, an Applanix POS MV (Position and Orientation System for Marine Vessels) was used to accurately position the vessels during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm). To account for tidal-cycle fluctuations, CSUMB used NavCom 2050 GPS receiver (CNAV) data, and Fugro Pelagos used KGPS data (GPS data with real-time kinematic corrections); in addition, sound-velocity profiles were collected with an Applied Microsystems (AM) SVPlus sound velocimeter. Soundings were corrected for vessel motion using the Applanix POS MV data, for variations in water-column sound velocity using the AM SVPlus data, and for variations in water height (tides) using vertical-position data from the KGPS receivers. Backscatter data were postprocessed using Geocoder version 3.2 (Fugro Pelagos modified test release 16). Within Geocoder, the backscatter intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. After the lines were corrected, they were mosaicked into a 1-m-resolution image. Overlap between parallel lines was resolved using a priority table whose values were based on the distance of each sample from the ship track, with the samples that were closest to and furthest from the ship track being given the lowest priority. An anti-aliasing algorithm was also applied. The mosaics were then exported as georeferenced TIFF images, imported into a geographic information system (GIS), and converted to GRIDs at 2-m resolution.

Processed soundings from the different mapping missions were exported from the acquisition or processing software as XYZ files and bathymetric surfaces. All the surfaces were merged into one overall 2-m-resolution bathymetric-surface model and clipped to the boundary of the map area. An illumination having an azimuth of 300° and from 45° above the horizon was then applied to the bathymetric surface to create the shaded-relief imagery (sheets 1, 2). In addition, a modified "rainbow" color ramp was applied to the bathymetry data for sheet 1, using reds and oranges to represent shallower depths, and blues to represent greater depths (note that the Offshore of San Gregorio 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). Gray areas in maps are gaps in data.

Bathymetric contours (sheets 1, 2, 3, 7, 10) were generated at 10-m intervals from the merged 2-m-resolution bathymetric surface. The most continuous contour segments were preserved; smaller segments and isolated island polygons were excluded from the final output. Contours were smoothed using a polynomial approximation with exponential kernel algorithm and a tolerance value of 60 m.

The backscatter grids were combined in a GIS to create an acoustic-backscatter map (sheet 3), on which brighter tones indicate higher backscatter intensity, and darker tones indicate lower backscatter intensity. The intensity represents a complex interaction between the acoustic pulse and the seafloor, as well as characteristics within the shallow subsurface, providing a general indication of seafloor texture and sediment type. Backscatter intensity depends on the acoustic source level; the frequency used to image the seafloor; the grazing angle; the composition and character of the seafloor, including grain size, water content, bulk density, and seafloor roughness; and some biological cover. Harder and rougher bottom types such as rocky outcrops or coarse sediment typically return stronger intensities (high backscatter, lighter tones), whereas softer bottom types such as fine sediment return weaker intensities (low backscatter, darker tones).

The onshore-area image was generated by applying an illumination having an azimuth of 300° and from 45° above the horizon to 1-m-resolution topographic-lidar data collected by Photoscience in 2005 for the U.S. Geological Survey and the County of San Mateo.

Chapter 3. Data Integration and Visualization for the Offshore of San Gregorio 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 San Gregorio 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 San Gregorio map area (sheet 4).

The maps and three-dimensional views on sheet 4 were created using a series of geographic information systems (GIS) and visualization techniques. Using GIS, the bathymetric and topographic data (sheet 1) were converted to ASCIIRASTER format files, and the acoustic-backscatter data (sheet 3) were converted to geoTIFF images. The bathymetric and topographic data were imported in the Fledermaus® software (QPS). The bathymetry was color-coded to closely match the colored shaded-relief bathymetry on sheet 1 in which reds and oranges represent shallower depths and blues represent deeper depths. Digital orthophotographs were draped over the topography data, and the acoustic-backscatter geoTIFF images were draped over the bathymetry data. The colored bathymetry, topography, and draped backscatter were then tilted and panned to create the perspective views such as those shown in figures 1, 2, 3, 5, 6, and 7 on sheet 4. These views highlight the seafloor morphology in the Offshore of San Gregorio map area, which includes exposed outcrops of fractured bedrock and complex patterns of shallow depressions.

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

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

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

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

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

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

The following four substrate classes are identified in the Offshore of San Gregorio map area:

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

The seafloor-character map of the Offshore of San Gregorio map area (sheet 5) was produced using video-supervised maximum-likelihood classification of the bathymetry and intensity of return from sonar systems, following the method described by Cochrane (2008). The two variants used in this classification were backscatter intensity and derivative rugosity, which is a standard calculation performed with the National Oceanic and Atmospheric Administration (NOAA) benthic-terrain modeler (available at http://www.csc.noaa.gov/digitalcoast/tools/btm/index.html; last accessed April 5, 2011), using a 3-pixel by 3-pixel array of bathymetry.

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

On the seafloor-character map (sheet 5), the four substrate classes have been colored to indicate the California MLPA depth zones and the Coastal and Marine Ecological Classification Standard (CMECS) slope zones (Madden and others, 2008) in which they belong. The California MLPA depth zones are Depth Zone 1 (intertidal), Depth Zone 2 (intertidal to 30 m), Depth Zone 3 (30 to 100 m), Depth Zone 4 (100 to 200 m), and Depth Zone 5 (greater than 200 m); in the Offshore of San Gregorio 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 San Gregorio map area, only Slope Class 1 is present. The final classified seafloor-character raster map image is 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 83.7 percent (89.8 km^2) of the map area: 48.5 percent (52.1 km^2) is in Depth Zone 2, and 35.2 percent (37.7 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 5.8 percent (6.2 km^2) of the map area: 3.1 percent (3.3 km^2) is in Depth Zone 2, and 2.7 percent (2.9 km^2) is in Depth Zone 3. Rock and boulder, rugose (rock outcrops and boulder fields having high surficial complexity) makes up 10.4 percent (11.2 km^2) of the map area: 6.5 percent (6.9 km^2) is in Depth Zone 2, and 4.0 percent (4.3 km^2) is in Depth Zone 3. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than surrounding seafloor) makes up 0.1 percent (0.1 km^2) of the map area: less than 0.1 percent (<0.1 km^2) is in both Depth Zone 2 and 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) and 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).

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 San Gregorio map area is covered predominantly by Class I sediment composed of soft, unconsolidated sand and mud. A sufficient number of video observations were made to complete accuracy assessment over sediment Classes I, II, and III. The Class IV areas in the Offshore of San Gregorio map area were assessed on the basis of sediment characteristics of similar areas to the north in the Offshore of Half Moon Bay map area, where video ground-truth-surveying data are available.

The classification accuracy of Classes I and III (64 percent and 59 percent accurate, respectively; table 4–2) is determined by comparing the shipboard video observations and the classified map. The weaker (54 percent accurate) agreement in Class II (mixed smooth sediment and rock and flat rock outcrop) likely is due to the relatively narrow and intermittent nature of transition zones from sediment to rock and also the size of the buffer; a strong likelihood exists for a Class II (mixed) pixel to be interspersed with pixels belonging to other classes. A single buffered observation locale of 78 pixels, therefore, is likely to be interspersed with other classes of pixels in addition to Class II. Percentages for presence/absence within a buffer also were calculated as a better measure of the accuracy of the classification for patchy rock habitat. The presence/absence accuracy was found to be significant for all classes (92 percent for Class I, 100 percent for Class II, and 97 percent for Class III). No video observations were retrieved over Class IV substrate in the map area; therefore, no accuracy assessment was performed for this class.

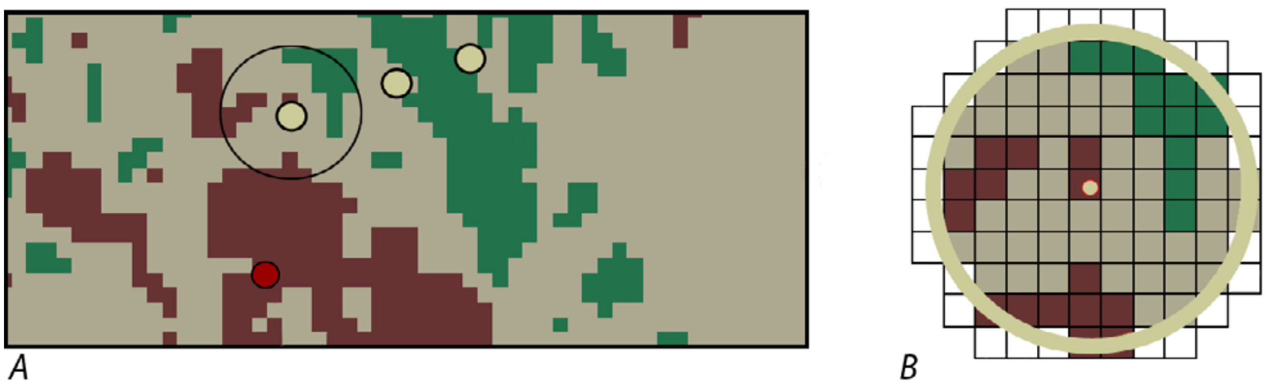

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted 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 San Gregorio map area.

[In areas of low visibility where primary and secondary substrate could not be identified with confidence, recorded observations of substrate (in fourth column) were used to assess accuracy]

Primary-substrate component	Secondary-substrate component	Abiotic seafloor complexity	Low-visibility observations
Class I			
sand	mud	low	
sand	sand	low	
sand	sand	moderate	
sand	shell hash	low	
			sediment
			ripples
Class II			
boulders	cobbles	low	
cobbles	mud	low	
cobbles	sand	low	
cobbles	sand	moderate	
mud	cobbles	low	
rock	rock	low	
rock	sand	low	
sand	boulders	moderate	
sand	cobbles	low	
sand	cobbles	moderate	
sand	rock	low	
sand	rock	moderate	
Class III			
boulders	boulders	high	
boulders	boulders	moderate	
boulders	cobbles	moderate	
boulders	rock	moderate	
boulders	sand	moderate	
cobbles	boulders	moderate	
rock	boulders	high	
rock	boulders	moderate	
rock	cobbles	moderate	

Table 4–1. Conversion table showing how video observations of primary substrate (more than 50 percent seafloor coverage), secondary substrate (more than 20 percent seafloor coverage), and abiotic seafloor complexity (in first three columns) are grouped into seafloor-character-map Classes I, II, and III for use in supervised classification and accuracy assessment in Offshore of San Gregorio map area.—*Continued*

[In areas of low visibility where primary and secondary substrate could not be identified with confidence, recorded observations of substrate (in fourth column) were used to assess accuracy]

Primary-substrate component	Secondary-substrate component	Abiotic seafloor complexity	Low-visibility observations
Class III—*Continued*			
rock	rock	high	
rock	rock	moderate	
rock	sand	moderate	
sand	boulders	high	

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

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

Class	Number of observations	% majority	% presence/absence
I—Fine- to medium-grained smooth sediment	214	63.5	91.6
II—Mixed smooth sediment and rock	69	54.4	100.0
III—Rock and boulder, rugose	218	59.4	96.8
IV—Medium- to coarse grained sediment (in scour depressions)	0	N/A	N/A

Chapter 5. Ground-Truth Studies for the Offshore of San Gregorio 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 San Gregorio map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred in 2007. The camera sled was towed 1 to 2 m over the seafloor, at speeds of between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 10.5 trackline kilometers of video and 675 still photographs, in addition to 611 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

During the ground-truth-survey cruise, 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 this cruise, in addition to recording the seafloor characteristics, a digital still photograph was captured once every 30 seconds.

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

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

substrate, slope, abiotic complexity, biotic complexity, and biotic cover are mandatory. Observations of key geologic features and the presence of key species also are made.

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

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

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

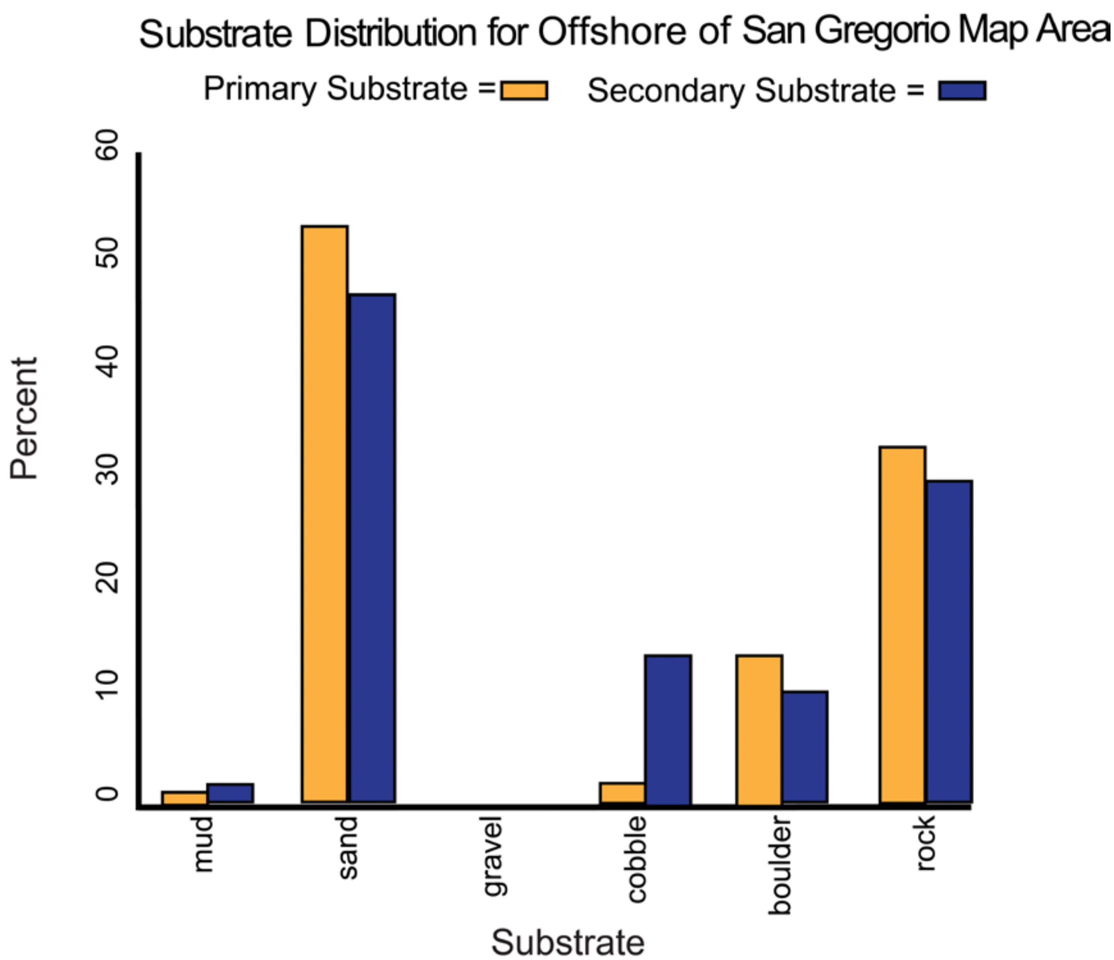

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of San Gregorio map area.

Chapter 6. Potential Marine Benthic Habitat Map of the Offshore of San Gregorio 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 San Gregorio 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 San Gregorio 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 San Gregorio 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, and Seafloor Complexity can be applied to habitat interpretations determined from seafloor samples, video, still photos, 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 San Gregorio map are explained in detail below (note, however, that not all categories may be used in a particular map area, given the study objectives, data availability, or data quality); attribute codes in each category are depicted on the map by the letters and, in some cases, numbers that make up the map-unit symbols:

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

E = Estuary (0 to 100 m)
S = Shelf; continental and island shelves (0 to 200 m)

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

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

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

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

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

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

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

Examples of Attribute Coding

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

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

Map Area Habitats

Delineated in the Offshore of San Gregorio map area are five potential marine benthic habitat types, all located on the continental shelf ("Shelf" megahabitat). The meso- and macrohabitats include deformed sedimentary-bedrock outcrops; a hard-soft mixed habitat type made up of flat, hard bedrock locally covered with soft, unconsolidated sediment; and dynamic features such as mobile sand sheets and associated scour depressions.

Most of the offshore part of the San Gregorio map area is located on the relatively flat and eroded continental shelf. Backscatter data show that the map area is dominated by "soft" sediment; however, the highly deformed and differentially eroded bedrock outcrops and their seafloor relief present the most spectacular backscatter imagery in this map area. These differentially eroded bedrock areas form the local relief and rugosity that make promising potential habitats for rockfish (*Sebastes* spp.). Sediment transport is primarily to the southeast, and sedimentary processes, which are quite active in the map area, produce the dynamic bedforms (primarily located along the periphery of hard bedrock exposures in the west-central part of the map area) that may be habitats for forage fish such as Pacific sand lance (*Ammodytes hexapterus*). In addition, erosion through shelf sediments down to a coarser lag has produced sediment-filled scour depressions that resemble "ripple scour depressions" of Cacchione and others (1984) and Phillips and others (2007), found mainly on the shelf in the northwestern and central parts of the map area.

Of the 107.75 km^2 in the map area, 14.44 km^2 (13.4 percent) is exposed hard bedrock, and 1.18 km^2 (1.1 percent) consists of sediment-covered bedrock, which is of the mixed hard-soft induration class. Soft, unconsolidated sediment covers a total of 92.13 km^2 (85.5 percent).

Chapter 7. Subsurface Geology and Structure of the Offshore of San Gregorio Map Area and the Bolinas to Pescadero Region (Sheets 8 and 9)

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

The seismic-reflection profiles presented on sheet 8 provide a third dimension, depth, to complement the surficial seafloor-mapping data already presented (sheets 1 through 7) for the Offshore of San Gregorio map area. These data, which are collected at several resolutions, extend to varying depths in the subsurface, depending on the purpose and mode of data acquisition. The seismic-reflection profiles (sheet 8) provide information on sediment character, distribution, and thickness, as well as potential geologic hazards, including active faults, areas prone to strong ground motion, and tsunamigenic slope failures. The information on faults provides essential input to national and state earthquake-hazard maps and assessments (for example, Petersen and others, 2008).

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

Data Acquisition

Most profiles displayed on sheet 8 (figs. 1, 2, 4, 5, 6, 7, 8, 9, 11) were collected in 2010 on U.S. Geological Survey (USGS) cruise S–15–10–NC. The profile shown in figure 3 was collected in 2007 on USGS cruise F–02–07–NC. During both cruises, the single-channel seismic-reflection data were acquired using the SIG 2Mille minisparker system, which used a 500-J high-voltage electrical discharge fired 1 to 4 times per second, which, at normal survey speed of 4 to 4.5 nautical miles/hour, gives a data trace every 0.5 to 2.0 m of lateral distance covered. The data were digitally recorded in standard SEG-Y 32-bit floating-point format, using Triton Subbottom Logger (SBL) software that merges seismic-reflection data with differential GPS-navigation data. After the survey, a short-window (20 ms) automatic gain control algorithm was applied to the data, along with a 160- to 1,200-Hz bandpass filter and a heave correction that uses an automatic seafloor-detection window (averaged over 30 m of lateral distance covered).

Figure 10 on sheet 8 shows a deep-penetration, migrated, multichannel seismic-reflection profile collected in 1976 by WesternGeco on cruise W–14–76–SF. This profile and other similar data were collected in many areas offshore of California in the 1970s and 1980s when these areas were considered a frontier for oil and gas exploration. Much of these data have been publicly released and are now archived at the U.S. Geological Survey National Archive of Marine Seismic Surveys (U.S. Geological Survey, 2009). These data were acquired using a large-volume air-gun source that has a frequency range of 3 to 40 Hz and recorded with a multichannel hydrophone streamer about 2 km long. Shot spacing was about 30 m. These data can resolve geologic features that are 20 to 30 m thick, down to subbottom depths of about 4 km.

Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of San Gregorio map area, herein considered part of the Pacifica-Pescadero shelf. This shelf (see Maps A, B on sheet 9), which is relatively flat (less than 0.7°) and shallow (64 m or less), is variably underlain by upper Pleistocene and

Holocene sediment deposited in the last about 21,000 years during the sea-level rise that followed the Last Glacial Maximum (LGM) and the last major lowstand. Sea level was about 125 m lower during the LGM, at which time the Offshore of San Gregorio map area was emergent and the shoreline was more than 45 km west of San Francisco, near the Farallon Islands. The post-LGM sea-level rise was rapid (about 9 to 11 m per thousand years) until about 7,000 years ago, when it slowed considerably to about 1 m per thousand years (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006; Gornitz, 2009).

The sediments deposited during this latest Pleistocene and Holocene sea-level rise are shaded blue in the seismic-reflection profiles on sheet 8 (figs. 6, 7, 8, 9, 11). This post-LGM stratigraphic unit is typically characterized either by “acoustic transparency” or by parallel, low-amplitude, low- to high-frequency, continuous to moderately continuous, diffuse reflections (terminology from Mitchum and others, 1977). The acoustic transparency (that is, lack of internal reflections) can be caused by extensive wave winnowing, resulting in a uniform sediment grain size, hence, the lack of acoustic-impedance contrasts needed to produce seismic reflections. The contact between these sediments and the underlying strata is a transgressive erosional surface, which commonly is marked by angularity, channeling, or a distinct upward change to lower amplitude, more diffuse reflections. It is emphasized that the base of this unit is an interpretation somewhat hindered by both acoustic transparency and by “acoustic masking,” which is associated with the presence of interstitial gas within the sediment (see, for example, Fader, 1997).

Geologic Structure and Recent Deformation

The Offshore of San Gregorio map area lies about 15 to 25 km southwest of the San Andreas Fault, the dominant structure in the distributed transform boundary between the North American and Pacific plates. The map area includes the right-lateral San Gregorio Fault system, the most important structure in the broad zone west of the San Andreas Fault. The San Gregorio Fault system extends for about 400 km from Point Conception on the south to Bolinas and Point Reyes on the north (Dickinson and others, 2005), predominantly in the offshore but also onshore at coastal promontories such as Pescadero Point in the map area and also at Pillar Point 14 km north of the map area, a few kilometers north of Half Moon Bay (see sheet 9; see also, Weber and Lajoie, 1980; Brabb and others, 1998). Offshore faults within this system are identified on seismic-reflection profiles on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as reflection presence, amplitude, frequency, geometry, continuity, and vertical sequence.

In the Offshore of San Gregorio map area, the San Gregorio Fault system forms a distributed shear zone about 2 to 4 km wide that includes two main diverging fault strands (see sheet 10). The west strand (also known as the “Frijoles Fault;” see figs. 1, 2, 3, 4, 5, 6, 7, 8, 10) extends offshore from Pescadero Point. The east strand (also known as the “Coastways Fault” or “Seal Cove Fault”) is mostly onshore in this map area; where it does go offshore, it is located too close to the shoreline to image with marine seismic-reflection data. Seismic-reflection data do show extensive faulting and folding of Neogene bedrock along the inner shelf between the west (Frijoles) and east (Coastways) strands of the San Gregorio Fault Zone (figs. 1 through 5). Paleoseismic data presented by Simpson and others (1997) suggested a post–late Pleistocene slip rate of 3.5 to 4.5 mm/yr for the onshore part of the east strand. This estimated slip rate represents a minimum because the offshore part of the west strand of the San Gregorio Fault Zone (Frijoles Fault) also is active. Cumulative lateral slip on the San Gregorio Fault Zone is thought to range from 4 to 10 mm/yr in this area (U.S. Geological Survey and California Geological Survey, 2010).

The west strand of the San Gregorio Fault Zone (Frijoles Fault) forms the east boundary of the Pigeon Point high (McCulloch, 1987) (see fig. 12 on sheet 8; see also, figs. 2, 4, 6, 7, 8, 9, 10, 11 on sheet 8), a bedrock ridge that extends offshore from Pescadero Point to the northwest. The Pigeon Point high is underlain by reflection-free (that is, massive and highly deformed) rocks of the Late Cretaceous Pigeon Point Formation that are unconformably overlain by mildly to highly reflective Neogene strata (figs. 2, 4, 6, 7, 8, 9, 10, 11 on sheet 8). Deeper penetrating, industry seismic-reflection data (fig. 10 on sheet 8) show the Pigeon Point high as an area that has very high amplitude reflection(s) near the seafloor, underlain by a relatively reflection-free zone that is bounded on the northeast and southwest by faults.

The Offshore of San Gregorio map area lies along strike with the young, high topography of the Santa Cruz Mountains and Coast Ranges (Maps C, D, E on sheet 9). This regional uplift has been linked to a northwest-transpressional bend in the San Andreas Fault about 15 to 25 km northeast of the map area (see, for example, Zoback and others, 1999). Rates of uplift of marine terraces of as much as 0.44 mm/yr near Año Nuevo, 15 km south of the map area, confirms that this ongoing regional uplift includes the coastal zone (Weber, 1990).

Map E shows the regional pattern of major faults and of earthquakes occurring between 1967 and March 2014 that have inferred or measured magnitudes of 2.0 and greater. Fault locations, which have been simplified, are compiled from our mapping within California's State Waters (see sheet 10) and from the U.S. Geological Survey's Quaternary fault and fold database (U.S. Geological Survey and California Geological Survey, 2010). Earthquake epicenters are from the Northern California Earthquake Data Center (2014), which is maintained by the U.S. Geological Survey and the University of California, Berkeley, Seismological Laboratory. Epicentral data indicate that recent seismicity in the Offshore of San Gregorio map area has been notably minimal. The largest number of earthquakes in the region clearly occur within the broad San Andreas Fault Zone between Pacifica and Bolinas; events west of the east strand of the San Gregorio Fault Zone and east of the Golden Gate Fault are much less common. Map E also shows the inferred location of the devastating great 1906 California earthquake (M7.8, 4/18/1906), thought to have nucleated on the San Andreas Fault offshore of San Francisco (see, for example, Bolt, 1968; Lomax, 2005).

Thickness and Depth to Base of latest Pleistocene and Holocene Deposits

Maps on sheet 9 show the thickness and the depth to base of uppermost Pleistocene and Holocene (post-LGM) deposits, both for the Offshore of San Gregorio map area (Maps A, B) and, to establish regional context, for a larger area (about 91 km of coast) that extends from the Bolinas area to Pescadero Point (Maps C, D). To make these maps, water bottom and depth to base of the LGM horizons were mapped from seismic-reflection profiles using Seisworks software. The difference between the two horizons was exported from Seisworks for every shot point as XY coordinates (UTM zone 10) and two-way travel time (TWT). The thickness of the post-LGM unit (Maps B, E) was determined by applying a sound velocity of 1,600 m/sec to the TWT, resulting in thicknesses as great as about 57 m. The thickness points were interpolated to a preliminary continuous surface, overlaid with zero-thickness bedrock outcrops (see sheet 10), and contoured (Wong and others, 2012).

Several factors required manual editing of the preliminary sediment-thickness maps to make the final product. The San Andreas, San Gregorio, and Golden Gate Faults disrupt the sediment sequence in the region (Maps D, E on sheet 9). The thickness data points also are dense along tracklines (about 1 m apart) and sparse between tracklines (1 km apart), resulting in contouring artifacts. To incorporate the effect of the faults, to remove irregularities from interpolation, and to reflect other geologic information and complexity, the resulting interpolated contours were modified. Contour modifications and regridding were repeated several times to produce the final regional sediment-thickness map (Wong and others, 2012). Information for the depth to base of the post-LGM unit (Maps A, C) was generated by adding the thickness data to water depths determined by multibeam bathymetry (see sheet 1).

The thickness of the post-LGM unit in the Offshore of San Gregorio map area ranges from 0 to 23 m (Map B on sheet 9), and the depth to the base of this unit ranges from less than 10 to 76 m (Map A on sheet 9). The most rapid changes in thickness are in the southern part of the map area along the west flank of the Pigeon Point high, offshore of Pescadero Point. Mean sediment thickness for the map area is 3.1 m, and the total sediment volume is 320×10^6 m^3 (table 7–1). The relatively thin sediment cover in most of the map area suggests a lack of sediment “accommodation space” (Catuneanu, 2006), which is consistent with regional uplift. The uplift raises and exposes much of the shallow shelf to the high wave energy that is characteristic of this region (Barnard and others, 2007), so that sediments are efficiently reworked and transported off the inner shelf and midshelf areas to deeper water.

Five different “domains” of sediment thickness are recognized on the regional sediment-thickness map (Map D on sheet 9): (1) the Bolinas shelf, located west of the east strand of the San Gregorio Fault Zone, in the northwestern part of the regional map (Map D); (2) the San Andreas graben, located between the San Gregorio Fault Zone and the Golden Gate Fault, east-southeast of the Bolinas shelf and both southwest and southeast of the Marin shelf; (3) the Marin shelf, located both northeast and northwest of the San Andreas graben and north of the San Francisco ebb-tidal delta paleovalley; (4) the northeast-trending San Francisco ebb-tidal delta paleovalley, located outside the Golden Gate at the mouth of San Francisco Bay, between the Marin shelf and San Andreas graben on the north and the Pacifica-Pescadero shelf on the south; and (5) the Pacifica-Pescadero shelf, which is located south of the San Francisco ebb-tidal delta paleovalley and which extends south all the way to Pescadero Point (including all of the Offshore of San Gregorio map area).

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

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

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

Regional sediment-thickness domains in Bolinas to Pescadero region			
	Area (km^2)	Mean sediment thickness (m)	Sediment volume (10^6 m^3)
Entire Bolinas to Pescadero region	529	6.2	3,286
(1) Bolinas shelf, west of east strand of San Gregorio Fault Zone	72	0.8	59
(2) San Andreas graben, between San Gregorio Fault Zone and Golden Gate Fault	27	33.5	906
(3) Marin shelf, northeast and northwest of San Andreas graben, north of San Francisco ebb-tidal delta paleovalley	44	8.1	355
(4) San Francisco ebb-tidal delta paleovalley	35	19.5	685
(5) Pacifica-Pescadero shelf	351	3.6	1,281
Sediment thickness in Offshore of San Gregorio map area			
Offshore of San Gregorio map area	102	3.1	320

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

By Janet T. Watt and Michael W. Manson

Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of San Gregorio 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), high-resolution seismic-reflection profiles (sheet 8), and aeromagnetic data (McCulloch and Chapman, 1977; U.S. Geological Survey, 2001).

Onshore geology was compiled from Brabb (1980), Weber and Lajoie (1980), California Geological Survey (1982, 2002b), Brabb and others (1998), and Witter and others (2006). Unit ages, which are derived from these sources, reflect local stratigraphic relations.

The continental shelf within California's State Waters in the Offshore of San Gregorio map area is shallow (less than about 55 m) and flat with a very gentle (less than 0.5°) offshore dip. Shelf morphology and evolution are the result of the interplay between local tectonics and sedimentation as sea level rose about 125 to 130 m during the last about 21,000 years (see, for example, Lambeck and Chappell, 2001; Gornitz, 2009), leading to the progressive eastward migration (a few tens of kilometers) of the shoreline and wave-cut platform and the associated transgressive erosion and deposition (see, for example, Catuneanu, 2006). The Offshore of San Gregorio map area is now an open-ocean shelf that is subjected to full, and sometimes severe, wave energy and strong currents. Shelf deposits are almost exclusively sand (unit Qms) at water depths less than 60 m, but, at greater depths in the southwestern part of the map area, they transition to the finer grained, muddy sediments of unit Qmsf. The boundary between units Qms and Qmsf is based on observations and extrapolation from sediment sampling (Reid and others, 2006) and camera ground-truth surveying (sheet 6). It is important to note that the boundary between units Qms and Qmsf should be considered transitional and approximate, as it likely shifts seaward or landward as a result of seasonal- to annual- to decadal-scale changes in sediment supply, sediment transport, and wave climate.

Coarser grained deposits (coarse sand and gravel) of units Qmss and Qmsc are recognized primarily on the basis of their high backscatter (see sheet 3). Unit Qmsc is mapped as a nearshore, shore-parallel bar at water depths typically between 5 and 10 m. Unit Qmss typically exists as erosional lags in scour depressions whose contacts with horizontal sand sheets of unit Qms usually are relatively sharp but, less commonly, also can be diffuse. These scour depressions, which generally form irregular to lenticular exposures that have abrupt landward contacts with bedrock, typically are a few tens of centimeters deep and range in size from a few tens of 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), where offshore sandy sediment is relatively thin (and, thus, is unable to fill the depressions) owing to low sediment supply and also to erosion and transport of sediment during large northwest winter swells.

Bedrock units mapped in the offshore include two units of the upper Miocene and Pliocene Purisima Formation (units Tp and Tpt). Rocks of the Purisima Formation are characterized by their high backscatter (sheet 3), as well as their distinct bedding style (caused by differential erosion), which is recognized in multibeam imagery and (or) or seismic-reflection data (see sheets 1, 2, 8). These Tertiary rocks are underlain by, or in fault contact with, Upper Cretaceous basement rocks, including sedimentary rocks of the Pigeon Point Formation (unit Kpp). The Pigeon Point Formation is mapped on the basis of its high backscatter, its massive and (or) rugged texture on multibeam imagery (sheets 1, 2), and its reflection-free character on seismic-reflection profiles (sheet 8). Offshore outcrops of the Pigeon Point Formation expose part of the Pigeon Point high (McCulloch, 1987).

In areas where bedrock is exposed on the seafloor but where less certainty exists regarding age, the undivided Cretaceous and Tertiary bedrock unit (TKu) is mapped. This undivided bedrock unit may include rocks of the Upper Cretaceous Pigeon Point Formation, the Oligocene and Miocene unnamed sedimentary and volcanic rocks unit (Tuv) (mapped onland near the mouth of Pescadero Creek), or the upper Miocene and Pliocene Purisima Formation.

In areas where shelf sediments form thin (less than 2.5 m) veneers over low-relief rocks of the undivided Cretaceous and Tertiary bedrock unit or the upper Miocene and Pliocene Purisima Formation, composite units Qms/TKu and Qms/Tp are mapped. These composite units are recognized on the basis of the combination of flat relief, continuity with moderate- to high-relief bedrock outcrops, high-resolution seismic-reflection data (sheet 8), and (in some cases) moderate to high backscatter. Overlying sediment is interpreted as an ephemeral and dynamic sediment layer that may or may not be continuously present, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term climate cycles. Storlazzi and others (2011) described the seasonal burial and exhumation of submerged bedrock in a similar high-energy setting in northern Monterey Bay, about 40 km south of the map area. The relative proportions of all offshore map units are shown in table 8–1.

The Offshore of San Gregorio map area lies about 15 to 25 km southwest of the San Andreas Fault, the dominant structure in the distributed transform boundary between the North American and Pacific plates. The map area straddles the right-lateral San Gregorio Fault system, a prominent structure west of the San Andreas Fault in the broader San Andreas Fault system. The San Gregorio Fault system extends for about 400 km from Point Conception on the south to Bolinas and Point Reyes on the north (Dickinson and others, 2005), predominantly in the offshore but also onshore at coastal promontories such as Pescadero Point in the map area and also at Pillar Point, 14 km north of the map area and a few kilometers north of Half Moon Bay (see sheet 9, Map E).

In the Offshore of San Gregorio map area, the San Gregorio Fault system forms a distributed shear zone about 2 to 4 km wide that includes two main diverging fault strands (fig. 1 on sheet 10). The west strand (also known as the Frijoles Fault), which extends offshore from Pescadero Point, forms the boundary between rocks of the upper Miocene and Pliocene Purisima Formation on the east and the undivided Cretaceous and Tertiary rocks (Pigeon Point Formation?) on the west. The east strand (also known as the Coastways Fault or Seal Cove Fault) is mostly onshore in this map area. Seismic-reflection profiles (see sheet 8) reveal that the offshore exposures of the Purisima Formation between the east and west strands of the San Gregorio Fault Zone are highly deformed compared to those of the undivided Cretaceous and Tertiary rocks west of the Frijoles Fault.

Cumulative lateral slip on the San Gregorio Fault system is thought to range from 4 to 10 mm/yr in this area (U.S. Geological Survey and California Geological Survey, 2010). The west strand of the San Gregorio Fault system (Frijoles Fault) forms the east boundary of the Pigeon Point high (McCulloch, 1987) (fig. 1 on sheet 10), a northwest-trending bedrock ridge that extends offshore for about 30 km from Pescadero Point and forms the northwest boundary of the Outer Santa Cruz Basin (McCulloch, 1987). The entire map area lies along strike with the young, high topography of the Santa Cruz Mountains and Coast Ranges (see sheet 9). This regional uplift has been linked to a northwest-transpressive bend in the San Andreas Fault (for example, Zoback and others, 1999). Rates of uplift of marine terraces of as much as 0.44 mm/yr near Año Nuevo, 15 km south of the map area, confirms that this regional uplift is ongoing and that it includes the coastal zone (Weber, 1990).

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

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine sedimentary units			
Qms	21,706,292	21.71	20.00
Qmsc	3,866,865	3.87	3.56
Qmss	323,990	0.32	0.30
Qmsf	500,654	0.50	0.46
Total, sedimentary units	26,397,801	26.40	24.32
Marine bedrock and (or) shallow bedrock units			
Qms/Tp	39,917,280	39.92	36.78
Qms/TKu	23,588,803	23.59	21.73
Tp	3,420,074	3.42	3.15
Tpt	129,245	0.13	0.12
TKu	727,261	0.73	0.67
Kpp	14,359,594	14.36	13.23
Total, bedrock units	82,142,257	82.14	75.68
Total, Offshore of San Gregorio map area	108,540,058	108.54	100.00

DESCRIPTION OF MAP UNITS

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Note that, where older units (typically, bedrock) are overlain by thin (<1 m thick) Quaternary deposits, composite units are mapped. These composite units, which are shown with gray 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; ripple marks common; found on seaward-dipping surface that extends from shoreline to west edge of map area

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

Qmss **Marine shelf scour depressions (late Holocene)**—Inferred to be coarse sand and possibly gravel; found as single depressions or in fields of depressions adjacent to bedrock or interspersed with elevated shelf sediments (unit Qms). General area in which unit is found is not likely to change substantially, but boundaries of unit(s) and locations of individual depressions (and intervening flat sheets) 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

Tp **Purisima Formation, undivided (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

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

TKu **Bedrock, undivided (Tertiary and Cretaceous)**—Possibly consists of rocks of the Pliocene and late Miocene Purisima Formation (units Tp, Tpt), the unnamed Miocene and Oligocene sedimentary and volcanic rocks unit (Tvu), or the Late Cretaceous Pigeon Point Formation (unit Kpp). Stippled areas (composite unit Qms/TKu) indicate where thin sheets of Qms overlie unit

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

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units are compiled from Brabb (1980), Weber and Lajoie (1980), Brabb and others (1998), and Witter and others (2006); unit ages, which are from these sources, reflect local stratigraphic relations. Locations of some faults are from California Geological Survey (1982, 2002b)]

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

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

afem **Artificial fill over estuarine mud (late Holocene)**—Material deposited by humans over estuarine sediment adf **Artificial-dam fill (late Holocene)**—Earth- or rock-fill dams, embankments, and levees; constructed to impound land-locked water bodies

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

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

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

Qyf **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

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

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

Qb **Basin deposits (Holocene)**—Fine-grained sediment that accumulates from standing or slow-moving water in topographic basins

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

Qyt **Stream-terrace deposits (Holocene)**—Relatively smooth, undissected terraces less than 8 to 10 m above active channel

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

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

Qoa **Older alluvial deposits, undivided (late Pleistocene)**—Alluvial fan or terrace surfaces; late Pleistocene age is indicated by depth of stream incision, degree of soil development, and lack of historical flooding

Qmt **Marine-terrace deposits, undivided (Pleistocene)**—Sand and gravel, deposited on uplifted marine-abrasion platforms along coast. Local relative ages designated by numbers from youngest (Qmt2) to oldest (Qmt1)

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

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

Qof **Older alluvial fan deposits (late to early Pleistocene)**—Moderately well to deeply dissected alluvial deposits; in places, original fan-surface morphology is preserved

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

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

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

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

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

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

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

Tuv **Unnamed sedimentary and volcanic rocks (Miocene and Oligocene)**—Mainly pebbly, crossbedded, hard arkosic sandstone in Pescadero Point area; grades to hard mudstone in Año Nuevo area, 15 km south of map area

Tmb **Mindego Basalt and related volcanic rocks (Miocene and Oligocene)**—Basaltic volcanic rocks, both extrusive and intrusive

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 rock that contains quartz and albite phenocrysts

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