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

By Janet T. Watt, Peter Dartnell, Nadine E. Golden, H. Gary Greene, Mercedes D. Erdey, Guy R. Cochrane, Samuel Y. Johnson, Stephen R. Hartwell, Rikk G. Kvitek, Michael W. Manson, Charles A. Endris, Bryan E. Dieter, Ray W. Sliter, Lisa M. Krigsman, Erik N. Lowe, and John L. Chin

(Janet T. Watt and Susan A. Cochran, editors)

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Contents

Figures

Tables

Map Sheets

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(Janet T. Watt[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 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 bathymetry 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

[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 February 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 Janet T. Watt

Regional Setting

The map area offshore of Point Reyes, California, which is referred to herein as the “Offshore of Point Reyes” map area (figs. 1–1, 1–2), occupies the western corner of the triangular Point Reyes peninsula. It is about 40 km north of San Francisco and about 50 km south of Fort Ross. The map area is in the northern part of the Gulf of the Farallones National Marine Sanctuary, and it includes all or parts of three California Marine Protected Areas (California Department of Fish and Wildlife, 2008): Point Reyes State Marine Reserve, Point Reyes State Marine Conservation Area, and Point Reyes Headlands Special Closure (fig. 1–2). The largely undeveloped onshore part of the map area, which occupies much of the southwestern part of the Point Reyes peninsula, is used primarily for grazing and formerly used for oyster farming in Drakes Estero, as well as recreation, as it is home to the Point Reyes National Seashore. The triangular Point Reyes peninsula, which lies completely west of the San Andreas Fault Zone, is bounded by the steep terrain of Inverness Ridge along its northeastern margin, Tomales Point at its northernmost tip, Point Reyes at its southwesternmost point, and Bolinas at its southern end. The coast and shoreline are scenic and diverse, ranging from the rolling hills and secluded sandy beaches that surround Drakes Bay and the estuaries of Drakes Estero and Estero de Limantour, to the steep, rocky granitic promontories at Point Reyes headland, up to the long, exposed windswept Point Reyes Beach, which is backed by an extensive dune field (figs. 1–1, 1–2).

Tectonic influences that impact the shelf morphology and geology in the map area are related to local faulting, folding, uplift, and subsidence. Offshore of the Point Reyes headland, granitic basement rocks are offset vertically about 1.4 km along the Point Reyes Fault Zone (McCulloch, 1987); this uplift combined with west-side-up offset on the San Andreas Fault Zone (Grove and Niemi, 2005), has resulted in uplift of the Point Reyes peninsula and the adjacent shelf (both the Bodega Head–Tomales Point shelf, north of the map area, and the Bolinas shelf; see sheet 9). The deformation associated with north-side-up motion across the Point Reyes Fault Zone has resulted in a distinct bathymetric gradient across the Point Reyes Fault Zone: an emergent or shallow bedrock platform is present to the north and east of the fault zone, and a deeper, submerged bedrock platform lies to the south. Late Pleistocene uplift of marine terraces on the southern Point Reyes peninsula suggests active deformation of offshore structures west of the San Andreas Fault Zone (Grove and others, 2010). Although the cumulative, post-Miocene slip rate on the Point Reyes Fault Zone in the map area is poorly constrained, it is estimated to be 0.3 mm/yr on the basis of vertical offset of granitic basement rocks (McCulloch, 1987; Wills and others, 2008).

The seafloor in the map area generally extends from the shoreline to water depths of about 40 to 60 m, except for the area south of the Point Reyes headland where water depths reach 60 to 70 m. This difference is the result of a distinct bathymetric gradient south and west of the Point Reyes headland, which is related to north-side-up motion along the Point Reyes Fault Zone (fig. 1–1). With the exception of the bathymetric gradient across the Point Reyes Fault Zone, the bedrock platform in the nearshore and inner shelf areas (50 to 60 m depth) north of the Point Reyes headland is relatively flat (less than 0.8°) and is overlain by sand-sized to coarser grained sediment. Finer grained sediments are found in water depths greater than 60 m south of the Point Reyes headland, but they also extend into shallower (less than 40 m) water within Drakes Bay. Surficial and shallow sediments were deposited in the last about 21,000 years during the approximately 125-m sea-level rise that followed the last major lowstand associated with the Last Glacial Maximum (Fairbanks, 1989; Fleming and others, 1998; Lambeck and

Chappell, 2001; Peltier and Fairbanks, 2006), at which time the entire Offshore of Point Reyes map area was emergent and the shoreline was about 30 km south and west of the present-day shoreline.

Potential marine benthic habitats in the Offshore of Point Reyes map area range from unconsolidated continental-shelf sediment to hard substrate, and they also include an area of sediment-covered hard mounds that may be marine debris. Rocky-shelf outcrops and rubble are considered to be promising potential habitats for rockfish (*Sebastes* spp.) and lingcod (*Ophiodon elongatus*) (Cass and others, 1990; Love and others, 2002), both of which are recreationally and commercially important species; in addition, the marine debris might provide good potential habitat for rockfish. Dynamic bedforms, such as the sand waves in northwestern Drakes Bay, are considered to be potential foraging habitat for juvenile lingcod and possibly migratory fishes (Beaudreau, 2005), as well as for forage fish such as Pacific sand lance (*Ammodytes hexapterus*).

Circulation over the continental shelf in the map area (and in the broader central California region) is dominated by the southward-flowing California Current, the eastern limb of the North Pacific Gyre (Hickey, 1979). Associated upwelling brings cool, nutrient-rich waters to the surface, resulting in high biological productivity. The current flow generally is southeastward during the spring and summer; however, during the fall and winter, the otherwise persistent northwest winds are sometimes weak or absent, causing the California Current to move farther offshore and the Davidson Current, a weaker, northward-flowing countercurrent (Hickey, 1979), to become active.

Sediment transport in the map area largely is controlled by surface waves and tidal currents in the nearshore and, at depths greater than 20 to 30 m, by tidal and subtidal currents. In the map area, nearshore littoral drift of sand and coarse sediment is to the south (Patsch and Griggs, 2007), owing to the dominant west-northwest swell direction, and scour from large waves and tidal currents removes and redistributes sediment over large areas of the inner shelf. Tidal currents are particularly strong over the shelf in the Offshore of Point Reyes map area, and they dominate the current regime in the nearshore (Noble and Gelfenbaum, 1990; Noble, 2001). Further offshore, bottom currents generally flow to the northwest, distributing finer grained sediment accordingly (Noble and Gelfenbaum, 1990).

Publication Summary

This publication about the Offshore of Point Reyes map area includes ten map sheets that contain explanatory text, in addition to this descriptive pamphlet and a data catalog of geographic information system (GIS) files. Sheets 1, 2, and 3 combine data from four different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data reveal a range of physiographic features (highlighted in the perspective views on sheet 4) such as the flat, sediment-covered seafloor in Drakes Bay, as well as abundant “scour depressions” on the Bodega Head–Tomales Point shelf (see sheet 9) 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 Salt Point to Drakes Bay region, interpreted on the basis of the seismic-reflection data, and it identifies the Offshore of Point Reyes map area as lying within the Bodega Head–Tomales Point shelf, Point Reyes bar, and Bolinas shelf domains. 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), as well as aerial-photographic interpretation of nearshore areas.

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.

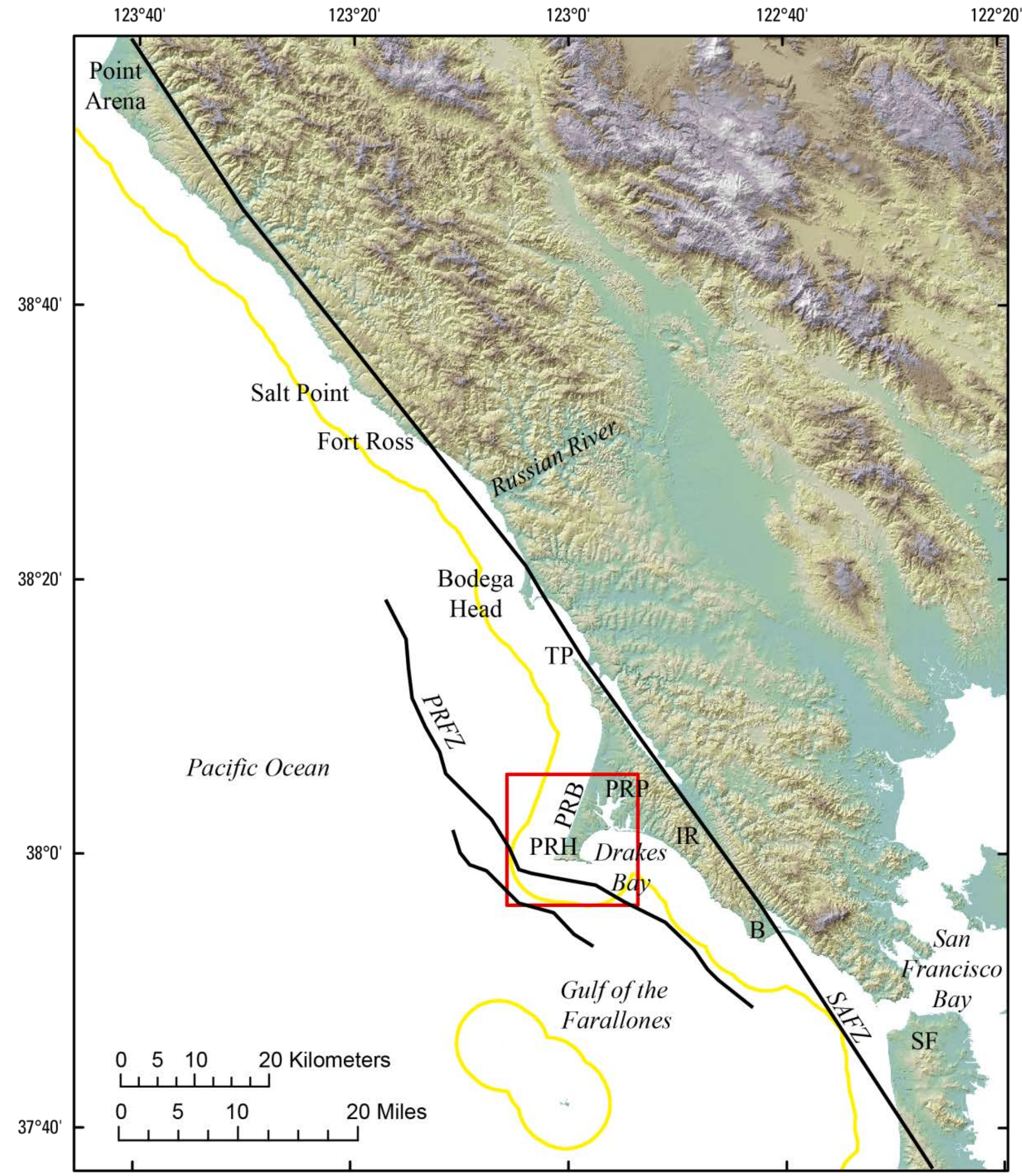

Figure 1–1. Physiography of northern California coast from Point Arena to San Francisco. Red box shows Offshore of Point Reyes map area. Yellow line shows limit of California's State Waters. Black lines show faults (PRFZ, Point Reyes Fault Zone; SAFZ, San Andreas Fault Zone). Other abbreviations: B, Bolinas; IR, Inverness Ridge; PRB, Point Reyes Beach; PRH, Point Reyes headland; PRP, Point Reyes peninsula; SF, San Francisco; TP, Tomales Point.

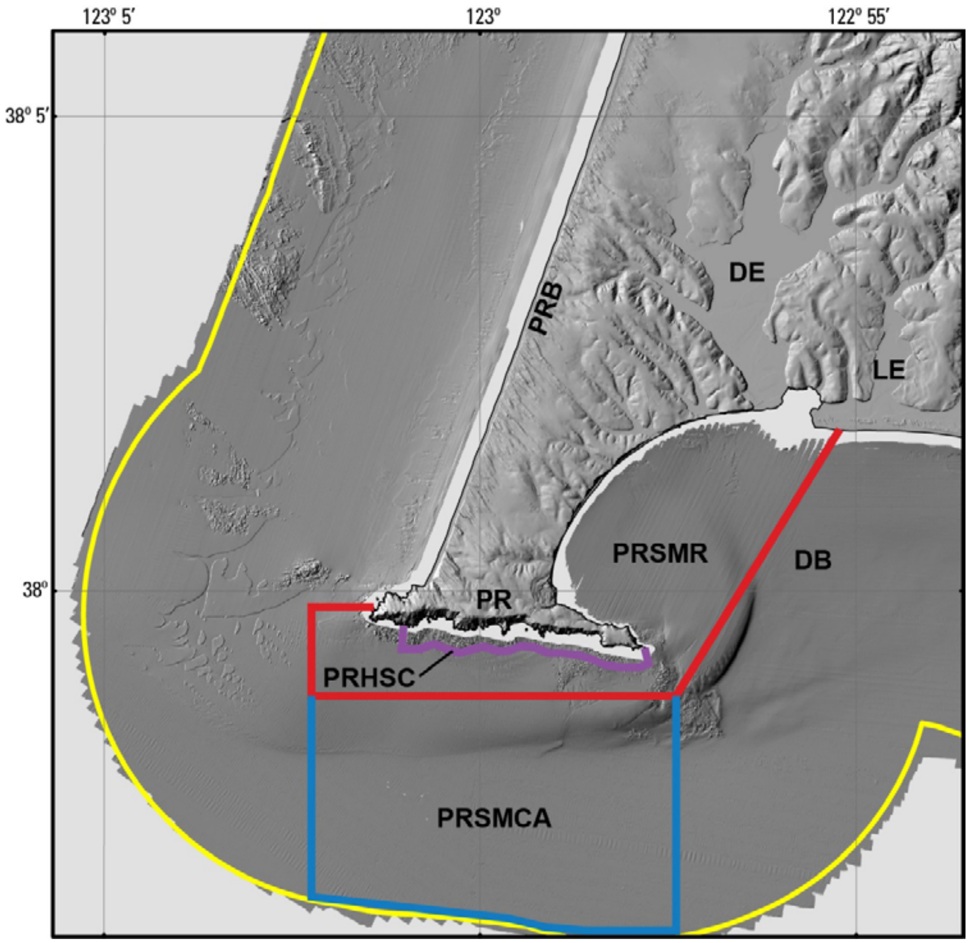

Figure 1–2. Coastal geography of Offshore of Point Reyes map area. Yellow line shows limit of California's State Waters. Indicated on map are California Marine Protected Areas: PRHSC, Point Reyes Headlands Special Closure (purple outline); PRSMCA, Point Reyes State Marine Conservation Area (blue outline); PRSMR, Point Reyes State Marine Reserve (red outline). Other abbreviations: DE, Drakes Estero; EL, Estero de Limantour; PR, Point Reyes; and PRB, Point Reyes Beach.

Chapter 2. Bathymetry and Backscatter-Intensity Maps of the Offshore of Point Reyes 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 Point Reyes 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). Mapping was completed between 2007 and 2010, using a combination of 200-kHz and 400-kHz Reson 7125 and 244-kHz Reson 8101 multibeam echosounders, as well as a 468-kHz SEA 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 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.

The multibeam-echosounder backscatter data were postprocessed using CARIS7.0/Geocoder software. Within Geocoder, the backscatter intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. After the lines were corrected, they were mosaicked into 1- or 2-m-resolution images. Overlap between parallel lines was resolved using a priority table whose values were based on the distance of each sample from the ship track, with the samples that were closest to and furthest from the ship track being given the lowest priority. An anti-aliasing algorithm was also applied. The mosaics were then exported as georeferenced TIFF images, imported into a geographic information system (GIS), and converted to GRIDs at 2-m resolution.

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

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 Point Reyes 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 straight lines that are apparent within the map area are data-collection 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 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 different mapping system and processing method were merged into their own individual grids. These individual grids, which cover different areas, were displayed in a GIS to create a composite acoustic-backscatter map (sheet 3). On the map, brighter tones indicate higher backscatter intensity, and darker tones indicate lower backscatter intensity. The intensity represents a complex interaction between the acoustic pulse and the seafloor, as well as characteristics within the shallow subsurface, providing a general indication of seafloor texture and 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 differences in backscatter intensity that are apparent in some areas on sheet 3 are due to the different frequencies of the mapping systems, as well as different processing techniques. Linear features of higher backscatter intensity throughout the map area are data-collection artifacts.

The onshore-area image was generated by applying an illumination having an azimuth of 300° and from 45° above the horizon to 3-m-resolution topographic-lidar data from the NOAA Coastal Service Center's Digital Coast (available at http://coast.noaa.gov/digitalcoast/) and 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 Point Reyes 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 Point Reyes 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 Point Reyes 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. Topographic data were shown in gray shades. The acoustic-backscatter geoTIFF images were also 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 through 6 on sheet 4. These figures highlight the seafloor morphology in the Offshore Point Reyes map area, which includes outcrops of fractured bedrock and complex patterns of shallow depressions.

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

Classes I, II, and III values were delineated using multivariate analysis. Class IV (medium- to coarse-grained sediment, in scour depressions) values were determined on the basis of their visual characteristics using both shaded-relief bathymetry and backscatter (slight depression in the seafloor, very high backscatter return). 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 Point Reyes 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 Point Reyes 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 76.0 percent (138.3 km^2) of the map area: 17.2 percent (31.2 km^2) is in Depth Zone 2, and 58.8 percent (107.1 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 14.9 percent (27.2 km^2) of the map area: 2.9 percent (5.4 km^2) is in Depth Zone 2, and 12.0 percent (21.8 km^2) is in Depth Zone 3. Rock and boulder, rugose (rock and boulder outcrops having high surficial complexity) makes up 2.9 percent (5.3 km^2) of the map area: 0.8 percent (1.5 km^2) is in Depth Zone 2, and 2.1 percent (3.8 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 6.2 percent (11.3 km^2) of the map area: 0.7 percent (1.2 km^2) is in Depth Zone 2, and 5.5 percent (10.1 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 Point Reyes map area is covered predominantly by Class I sediment composed of sand and mud; in addition, several large areas of Class II coarse sediment (coarse sand, gravel, and cobbles) are present. Several small exposures of rugose bedrock (Class III) are present in the nearshore near the Point Reyes headland and also further offshore, west of the Point Reyes peninsula. The rock 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) are present throughout the western part of the map area.

The classification accuracies of Class I, II, and IV sediments (72, 73, and 88 percent accurate, respectively; table 4–2) are determined by comparing the shipboard video observations and the classified map. The weaker agreement in Class III (43 percent accurate) 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 classification for patchy rock habitat. The presence/absence accuracy was found to be significant for all classes (90 percent for Class I, 95 percent for Class II, 78 percent for Class III, and 91 percent for Class IV).

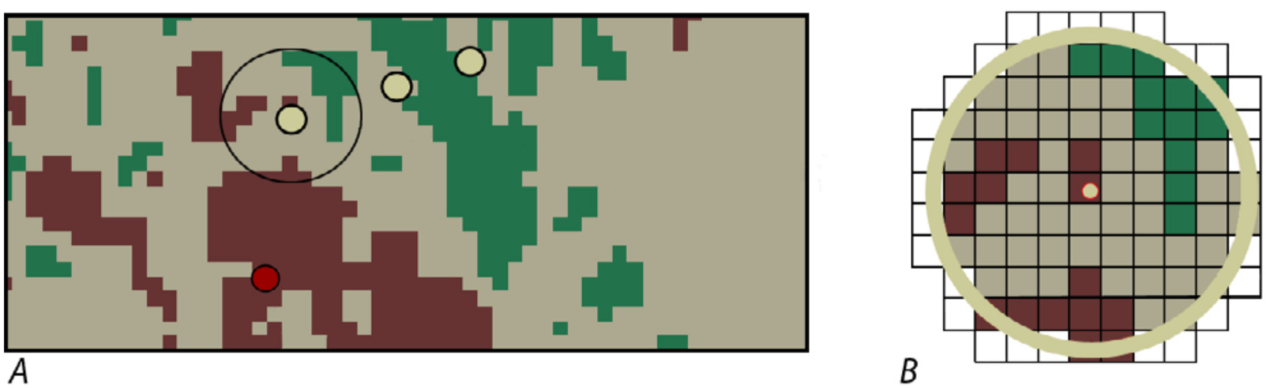

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

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

[Accuracy assessments are based on video observations]

Class	Number of observations	% majority	% presence/absence
I—Fine- to medium-grained smooth sediment	447	72.4	89.5
II—Mixed smooth sediment and rock	81	72.9	95.1
III—Rock and boulder, rugose	134	42.7	77.6
IV—Medium- to coarse-grained sediment (in scour depressions)	45	88.3	91.1

Chapter 5. Ground-Truth Studies for the Offshore of Point Reyes 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 Point Reyes map area to collect video and photographic data that would "ground truth" the seafloor. This ground-truth surveying occurred in 2007 and 2008. 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 18 trackline kilometers of video and 713 still photographs, in addition to 748 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

During the 2007 and 2008 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

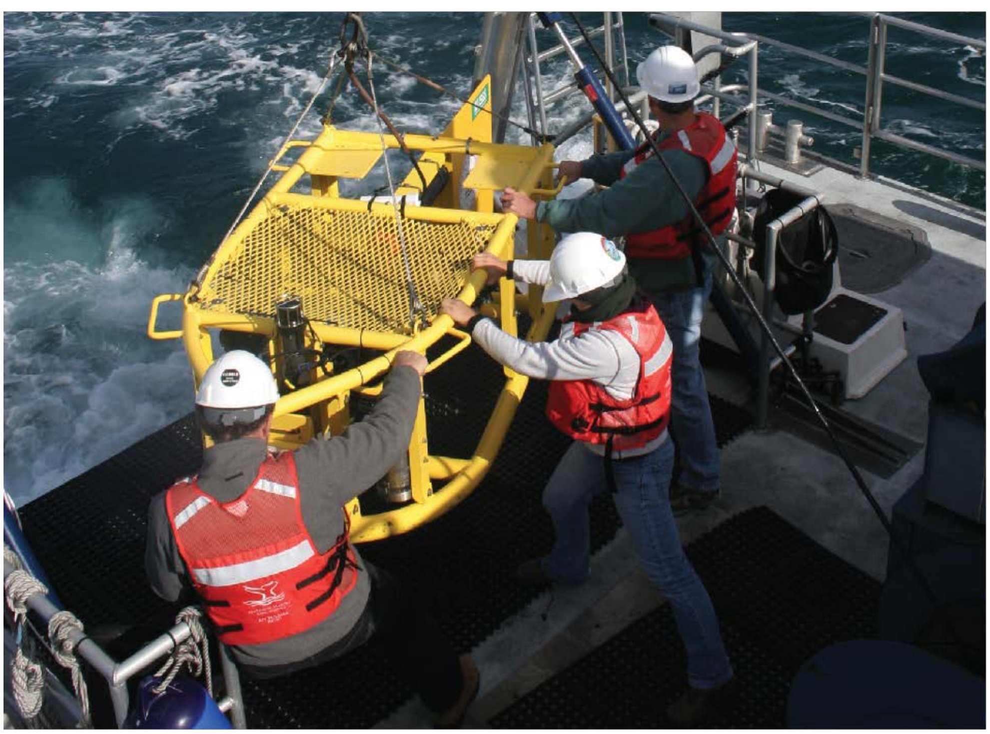

Figure 5–1. Photograph of camera sled used in USGS 2007 ground-truth survey.

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 D); for each view, the box shows the locations (indicated by colored stars) of representative seafloor photographs. For each photograph, an explanation of the observed seafloor characteristics recorded by USGS and NOAA scientists is given. Note that individual photographs often show more substrate types than are reported as the primary and secondary substrate. Organisms, when present, are labeled on the photographs.

The ground-truth survey is designed to investigate areas that represent the full spectrum of high-resolution multibeam bathymetry and backscatter-intensity variation. Figure 5–2 shows that, in the Offshore of Point Reyes map area, the seafloor surface is predominantly fine-grained sandy sediment (see also, figs. 3B, 4I on sheet 6). Nearshore areas of rocky outcrop can be seen along wave-exposed areas of the coast west and south of the Point Reyes headland (see figs. 2C, 2D on sheet 6). In the northwestern part of the map area, large areas of rocky outcrop, which are related to regional faulting (see sheet 10), are present in deeper water (see fig. 1F on sheet 6).

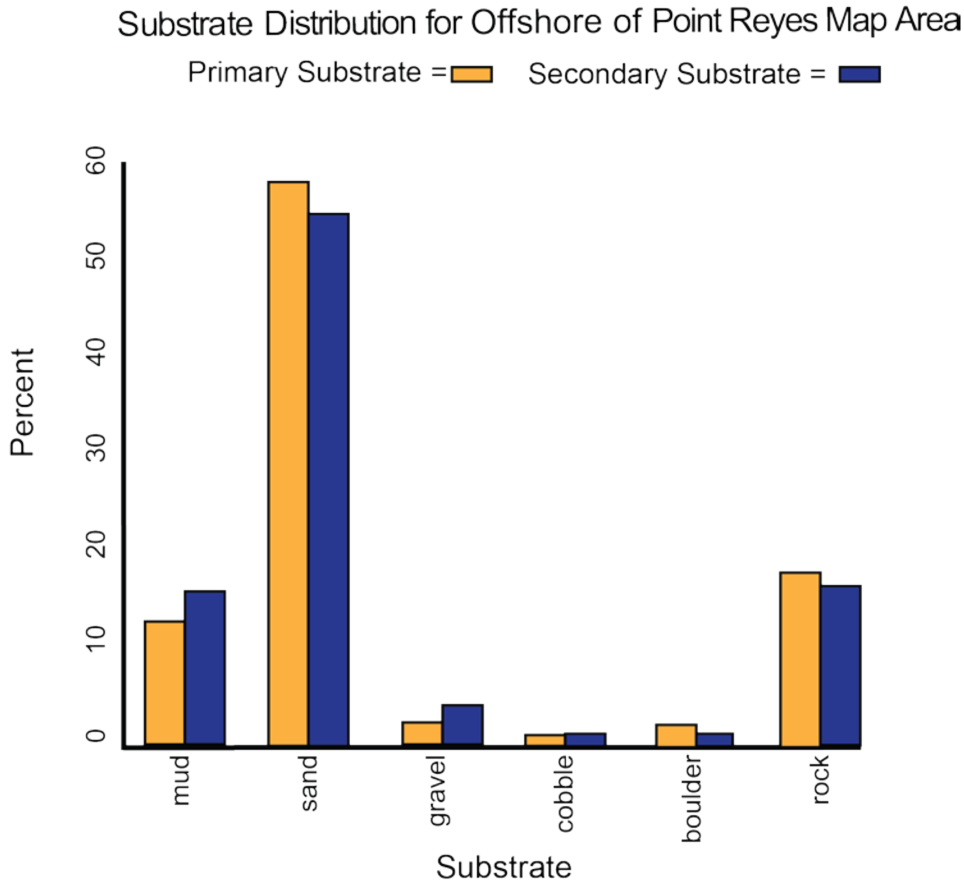

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Point Reyes map area.

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

By H. Gary Greene, Charles A. Endris, and Bryan E. Dieter

The map on sheet 7 shows “potential” marine benthic habitats in the Offshore of Point Reyes 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 Point Reyes 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) are also 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 Point Reyes 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 Point Reyes 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 = Beach, relic (submerged) or shoreline
(b)/p = Pinnacle indistinguishable from boulder
d = Deformed, tilted and (or) folded bedrock; overhang
e = Exposure; bedrock
h = Hole; depression
m = Mound; linear ridge
p = Pinnacle; cone
s = Scarp, cliff, fault, or slump scar
w = Dynamic bedform
y = Delta; fan

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 hyphen or in parentheses (or both), following an underscore; multiple attributes separated by slash.

_a = Anthropogenic (artificial reef, breakwall, shipwreck, disturbance)
  _a-dg = Dredge groove or channel
  _a-g = Groin, jetty, rip-rap
  _a-w = Wreck, ship, barge, or plane
_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 Point Reyes map area are 18 potential marine benthic habitat types, covering 182.40 km^2 on the continental shelf (“Shelf” megahabitat). These include unconsolidated sediments (11 habitat types), mixed substrate (2 habitat types), hard substrate (4 habitat types), and a possible anthropogenic feature (1 habitat type). The predominant habitat type is soft, unconsolidated sediment, covering 170.72 km^2 (93.6 percent). Exposed hard bedrock covers 10.02 km^2 (5.5 percent); sediment-covered bedrock, which is of the mixed hard-soft induration class, covers 1.16 km^2 (0.6 percent); sediment-covered mounds of unidentified anthropogenic(?) material, possibly related to marine debris, cover 0.5 km^2 (0.3 percent). Rock outcrops and rubble are considered the primary habitat types for rockfish (*Sebastes* spp.) and lingcod (*Ophiodon elongatus*) (Cass and others, 1990; Love and others, 2002), both of which are recreationally and commercially important species.

Chapter 7. Subsurface Geology and Structure of the Offshore of Point Reyes Map Area and the Salt Point to Bolinas 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, to complement the surficial seafloor-mapping data already presented (sheets 1 through 7) for the Offshore of Point Reyes 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, 3, 5, 7, 9) were collected in 2009 on U.S. Geological Survey (USGS) cruise S–8–09–NC. The single-channel seismic-reflection data were acquired using the SIG 2Mille minisparker that 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).

Figures 6 and 8 on sheet 8 show deep-penetration, depth-converted, 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. Most 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 Point Reyes map area. The seafloor in this area extends from the shoreline to water depths of about 40 to 50 m, except for the area south of the Point Reyes headland, where water depths reach 60 to 70 m. This difference is the result of a distinct bathymetric gradient across the Point Reyes headland, which is related to north-side-up motion on the Point Reyes Fault Zone (fig. 1–1). The bedrock platform in the map area is relatively flat (less than 1.0°)

and overlain by thin sediment cover, except for the area around the Point Reyes headland, where a large nearshore bar has formed, and also south of the Point Reyes headland, where the seafloor crosses the Point Reyes Fault Zone.

The Offshore of Point Reyes map area is characterized by granitic and metamorphic basement rocks of the Salinian block and overlying Tertiary marine sedimentary rocks of the Bodega Basin (McCulloch, 1987) and the Point Reyes Syncline (Weaver, 1949), all of which have been uplifted and deformed along the Point Reyes Fault Zone, forming the present-day Point Reyes peninsula. These different rock types can be mapped on the seafloor (see sheet 10) on the basis of their distinctive surface morphologies. Granitic seafloor outcrops are characterized by their massive, bulbous texture, and they are cut by a dense network of fractures and small faults. In contrast, the overlying folded Tertiary sedimentary rocks are characterized by a "ribbed" morphology that results from the variable resistance to erosion of different beds (lithologies) within the sedimentary sections. Offshore of Point Reyes Beach, in the northwestern part of the map area, the sedimentary rocks are less "ribbed," owing to their shallower dips (see sheet 10).

On seismic-reflection data, the Late Cretaceous granitic rocks and the early Eocene (Clark and Brabb, 1997) Point Reyes Conglomerate of Galloway (1977) are nonreflective. The overlying Neogene section (mapped as the undivided sedimentary rocks unit [Tu] and the Purisima Formation [Tp] on sheet 10) is characterized by continuous, parallel to subparallel, variable amplitude, high-frequency reflections (terminology from Mitchum and others, 1977), except for a zone of chaotic low-amplitude reflections (see fig. 2 on sheet 8). This zone of chaotic reflections may represent more massive (that is, lacking bedding) sedimentary rocks within either the Monterey Formation or the Santa Cruz Mudstone, or it may represent the Santa Margarita Sandstone.

Surficial and shallow sediments were deposited in the last about 21,000 years during the sea-level rise that followed the last major lowstand associated with the Last Glacial Maximum (LGM) (Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006). Sea level was about 125 m lower during the LGM, at which time the Offshore of Point Reyes map area was emergent. The post-LGM sea-level rise was rapid (about 9 to 11 m per thousand years) until about 7,000 years ago, when it slowed considerably to about 1 m per thousand years (Peltier and Fairbanks, 2006; Stanford and others, 2011).

The sediments deposited during the post-LGM sea-level rise (the rapid transgression and highstand) are shaded blue in the high-resolution seismic-reflection profiles on sheet 8 (figs. 1, 2, 3, 5, 7, 9), and their thickness is shown on sheet 9 (Maps B, D). Two distinct sediment sequences are present within the post-LGM unit: (1) West and southwest of the Point Reyes headland, low-amplitude, prograding clinoforms overlie parallel, gently dipping reflectors that are visible in high-resolution seismic-reflection profiles (figs. 1, 2, 3 on sheet 8); the clinoforms are interpreted to represent the nearshore bar that wraps around the Point Reyes headland and into Drakes Bay. The bar is continuous except offshore of the east end of the Point Reyes headland, where granitic rocks are exposed on the seafloor. The limit of the bar is denoted by a break in slope that is visible both on multibeam bathymetry imagery (see sheet 1) and on high-resolution seismic-reflection profiles (see sheet 8). The bar is located south of the east-west-trending Point Reyes headland, which once was emergent when sea level was lower but now is partly submerged. Deposition of the bar likely began as sea level was rising, and its extent migrated eastward as sea level rose and the west end of that bedrock ridge was submerged below wave base. (2) At the base of the uppermost Pleistocene and Holocene unit are inferred transgressive-systems-tract deposits (Catuneanu, 2006), which are characterized by channeling and various progradational patterns (see, for example, figs. 7, 9 on sheet 8). These deposits likely represent deposition within an estuarine environment, similar to the nearby Drakes Estero and Estero de Limantour.

Geologic Structure and Recent Deformation

Faults in the offshore part of the Offshore of Point Reyes map area 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. The Point Reyes Fault Zone, which runs through the map area in the offshore, is a curvilinear reverse fault zone that has predominantly north-side-up motion (Hoskins and Griffiths, 1971; McCulloch, 1987; Heck and others, 1990; Stozek, 2012); this fault likely connects at depth with the west strand of the San Gregorio Fault Zone south of the map area (Ryan and others, 2008), which means that it is part of the San Andreas Fault system. The Point Reyes Fault Zone is characterized by a 5- to 11-km-wide zone of deformation in the shallow subsurface that is associated with two main fault structures, which are imaged with deep-penetration industry multichannel seismic data: the Point Reyes Fault, and also a west strand mapped offshore of the Point Reyes peninsula (see fig. 4 on sheet 8). Near the Point Reyes headland, vertical displacement of granitic basement rocks across the Point Reyes Fault is at least 1.4 km (McCulloch, 1987). The west strand of the Point Reyes Fault Zone is defined by a broad anticlinal structure, which is visible in both industry and high-resolution seismic data (see figs. 3, 6, 7, 8, 9 on sheet 8). The west strand exhibits the same sense of vergence (north side up) as that of the Point Reyes Fault. In the map area, the cumulative (since late Miocene) slip rate on the Point Reyes Fault Zone is poorly constrained, but it is estimated to be 0.3 mm/yr on the basis of vertical offset of granitic basement rocks (McCulloch, 1987; Wills and others, 2008).

A distinct unconformity (or acoustic-impedance contrast) between the upper Miocene and Pliocene Purisima Formation and younger sediments is otherwise lacking in the map area, making the distribution of upper Pliocene and Pleistocene strata difficult to ascertain from seismic-reflection data. However, lithological and paleontological data from Shell Oil Company offshore well 39–1, which was drilled into the crest of the anticline above the west strand of the Point Reyes Fault Zone (see fig. 7 on sheet 8), suggest that about 220 m of upper Pliocene and Pleistocene sediments overlie the Purisima Formation (Webster and Yenne, 1987; Heck and others, 1990) and that the upper 80 m is interpreted as being of Quaternary age (Webster and Yenne, 1987). If this is the case, then a significant amount of post–Purisima Formation strata is present on the shelf south of the Point Reyes headland that has been deformed within the Point Reyes Fault Zone. Lack of clear deformation within the post-LGM unit suggests that activity along the Point Reyes Fault Zone has diminished or slowed since about 21,000 years ago.

Map E on sheet 9 shows the regional pattern of major faults and earthquakes. Fault location is simplified and compiled from our mapping (see sheet 10) and from the U.S. Geological Survey's Quaternary fault and fold database (U.S. Geological Survey and California Geological Survey, 2010). Earthquake epicenters are from the Northern California Earthquake Data Center (2014), which is maintained by the U.S. Geological Survey and the University of California, Berkeley, Seismological Laboratory; all events of magnitude 2.0 and greater for the time period 1967 through March 2014 are shown. The largest earthquake in the map area (M2.9, 4/13/1970) was located about 3.8 km southeast of the Point Reyes headland. A notable lack of microseismicity on the adjacent San Andreas Fault has occurred since 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), about 40 km south of the map area.

Thickness and Depth to Base of Uppermost Pleistocene and Holocene Deposits

Maps on sheet 9 show the thickness and the depth to base of uppermost Pleistocene and Holocene (post-LGM) deposits, both for the Offshore of Point Reyes map area (Maps A, B) and, to establish regional context, for a larger area (about 115 km of coast) that extends from the Salt Point area south to the southern part of the Point Reyes peninsula (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, D) was determined by applying a sound velocity of 1,600 m/sec to the TWT, resulting in thicknesses as great as about 56 m. The thickness points were interpolated to a preliminary continuous surface, overlaid with zero-thickness bedrock outcrops (see sheet 10), and contoured following the methodology of Wong and others (2012).

Several factors required manual editing of the preliminary sediment-thickness maps to make the final product. The Gualala, Point Reyes, and San Andreas 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 on sheet 9) 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 Point Reyes map area ranges from 0 to 30 m (Map B on sheet 9), and the depth to the base of this unit ranges from 0 to 90 m (Map A on sheet 9). Mean sediment thickness for the map area is 8.0 m, and the total sediment volume is $1{,}386\times10^{6}$ m^{3} (table 7–1). A distinct bathymetric gradient is present across the Point Reyes Fault south of the Point Reyes headland and the adjacent, submerged, bedrock outcrops of the Point Reyes Conglomerate: a shallow bedrock platform lies to the north and east of the fault, and a deeper bedrock platform lies to the south. The accommodation space created by offset on the Point Reyes Fault allowed as much as 30 m of uppermost Pleistocene and Holocene sediment to be trapped and stored south and west of the Point Reyes headland.

The thickest deposits are found at water depths of about 40 to 60 m where nearshore-bar deposits overlie deeper water deposits in what is referred to as the Point Reyes bar (see Maps A, B on sheet 9). The nearshore-bar deposits are characterized by low-amplitude, prograding clinoforms, which are visible in high-resolution seismic profiles. The Point Reyes bar likely formed in the lee of the Point Reyes headland during rising sea level. These nearshore deposits overlie parallel, gently seaward-dipping reflectors (see sheet 8), which likely were deposited in deeper water (below wave base). The deeper water deposits reach a maximum thickness of about 25 m in two locations: (1) southwest of the Point Reyes headland, along the synclinal axis just south of the Point Reyes Fault, and (2) directly south of the Point Reyes headland, in water depths of between 60 to 70 m. The likely source of the deeper water deposits is from the adjacent Drakes Estero and Estero de Limantour and (or) from northwestward transport of sediment from San Francisco Bay (Noble and Gelfenbaum, 1990).

Very little sediment cover is present on the seafloor north and east of the Point Reyes Fault. The Bodega Head–Tomales Point shelf is covered by only a thin veneer (less than 2.5 m) of sediment. The Bolinas shelf also is relatively devoid of sediment, except within a depocenter present in Drakes Bay offshore of Drakes Estero and Estero de Limantour where sediment thickness reaches 15 m. This depocenter is bounded on the southeast by an east-northeast-trending ridge on the Bolinas shelf. The lack of sediment on the Bodega Head–Tomales Point and Bolinas shelves reflects a combination of limited sediment supply and lack of sediment accommodation space. Despite the limited sediment-storage space on the Bodega Head–Tomales Point shelf, the long, west-facing beach located north of the

Point Reyes headland, Point Reyes Beach, has had a long-term (from the mid- to late-1800s to 1902) history of accretion, at rates of 0.1 to 1.0 m/yr (Hapke and others, 2006).

Five different "domains" of sediment thickness are recognized on the regional sediment-thickness map (Map D on sheet 9), each with distinctive geologic controls: (1) The Salt Point shelf domain, located in the far northwestern part of the region, has a mean sediment thickness of 11.7 m. The thickest sediment (20 to 25 m) is found where a pre-LGM, regressive, downlapping sediment wedge formed above a break in slope that is controlled by a contact between harder bedrock and softer, folded Pleistocene strata. Sediment thinning in this domain within the outer parts of California's State Waters is the result of a relative lack of sediment supply from local watersheds, as well as a more distal Russian River source. (2) The Russian River delta and mud belt domain, located offshore of the Russian River, the largest sediment source on this part of the coast, has the thickest uppermost Pleistocene and Holocene sediment in the region (mean thickness, 21.1 m). The northward extension into the midshelf "mud belt" results from northward shelf-bottom currents and sediment transport (Drake and Cacchione, 1985). This domain includes a section of the San Andreas Fault Zone, which here is characterized by several releasing, right-stepping strands that bound narrow, elongate pull-apart basins; these sedimentary basins contain the greatest thickness of uppermost Pleistocene and Holocene sediment (about 56 m) in the region. (3) The Bodega Head–Tomales Point shelf domain, located between Bodega Head and the Point Reyes headland, contains the least amount of sediment in the region (mean thickness, 3.4 m). The lack of sediment primarily reflects decreased accommodation space and limited sediment supply. (4) The Point Reyes bar domain, located west and south of the Point Reyes headland, is a local zone of increased sediment thickness (mean thickness, 14.3 m) created by bar deposition on the more protected south flank of the Point Reyes headland during rising sea level. (5) The Bolinas shelf domain, located east and southeast of the Point Reyes headland, has a thin sediment cover (mean thickness, 5.6 m), which likely reflects a limited sediment "accommodation space" (Catuneanu, 2006) caused by tectonic uplift (water depths in this domain within California's State Waters are less than 45 m) and also high wave energy capable of reworking and transporting shelf sediment to deeper water.

Table 7–1. Area, sediment-thickness, and sediment-volume data for California's State Waters in Salt Point to Drakes Bay region (domains 1–5), as well as in Offshore of Point Reyes map area.

Regional sediment-thickness domains in Salt Point to Drakes Bay region			
	Area (km^2)	Mean sediment thickness (m)	Sediment volume (10^6 m^3)
Entire Salt Point to Drakes Bay region	714	9.5	6,794
(1) Salt Point shelf	90	11.7	1,054
(2) Russian River delta and mud belt	144	21.1	3,031
(3) Bodega Head–Tomales Point shelf	275	3.4	928
(4) Point Reyes bar	72	14.3	1,029
(5) Bolinas shelf	133	5.6	752
Sediment thickness in Offshore of Point Reyes map area			
Offshore of Point Reyes map area	176	8.0	1,386
Bodega Head–Tomales Point shelf	59	1.4	81
Point Reyes bar	72	14.3	1,029
Bolinas shelf	45	6.2	276

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

By Janet T. Watt, Michael W. Manson, and H. Gary Greene

Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Point Reyes 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.

Onshore bedrock mapping is compiled from Clark and Brabb (1997) and Wagner and Gutierrez (2010); unit ages, which are derived from these sources, reflect local stratigraphic relations. Onshore Quaternary mapping is compiled from Witter and others (2006) and Wagner and Gutierrez (2010), with some additional mapping by M.W. Manson (this report); in addition, some units are modified by M.W. Manson on the basis of analysis of 2012 lidar imagery.

The onshore part of the Offshore of Point Reyes map area contains the southwestern part of the Point Reyes peninsula, which is located entirely west of the San Andreas Fault, the transform boundary between the Pacific and North American plates. The Point Reyes peninsula is composed of Late Cretaceous granitic rocks of the Salinian block that are overlain by Tertiary marine sedimentary rocks (Page, 1982). The Salinian block, an allochthonous (that is, out of place) tectonostratigraphic terrane, was brought north to its present-day position by right-lateral slip along the San Andreas Fault system. Since late Miocene time, the Point Reyes peninsula has been offset about 155 km along the San Gregorio and San Andreas Faults from the Monterey peninsula, where it was adjacent to Point Lobos (Greene and Clark, 1979; Clark and others, 1984; Dickinson and others, 2005).

The geology and geomorphology of the Offshore of Point Reyes map area are the result of the interplay between tectonics, sea-level rise, local sedimentary processes, and oceanography. The Point Reyes Fault Zone, which runs through the offshore part of the map area, is a curvilinear reverse fault zone (Hoskins and Griffiths, 1971; McCulloch, 1987; Heck and others, 1990; Stozek, 2012) that likely connects with the west strand of the San Gregorio Fault Zone farther south (Ryan and others, 2008), making it part of the San Andreas Fault system. The Point Reyes Fault Zone is characterized by a 5- to 11-km-wide zone that is associated with two main fault structures: the Point Reyes Fault, and also a west strand mapped offshore of the Point Reyes peninsula (see fig. 1–1).

Tectonic influences that affect shelf morphology and geology are local faulting, folding, uplift, and subsidence. Offshore of the Point Reyes headland, granitic basement rocks are offset vertically (north side up) about 1.4 km on the reverse-slip Point Reyes Fault Zone (McCulloch, 1987); this uplift, combined with west-side-up offset on the San Andreas Fault Zone (Grove and Niemi, 2005), has resulted in uplift of the Point Reyes peninsula and the adjacent shelf (both the Bodega Head–Tomales Point shelf, north of the map area, and the Bolinas shelf; see sheet 9). The west strand of the Point Reyes Fault Zone is defined by a broad anticlinal structure, which is visible in both industry and high-resolution seismic-reflection data (see sheet 8), and it exhibits the same sense of vergence (north side up) as that of the Point Reyes Fault. The deformation associated with north-side-up motion across the Point Reyes Fault Zone has resulted in a distinct bathymetric gradient across the Point Reyes Fault

Zone: an emergent or shallow bedrock platform is present to the north and east of the fault zone, and a deeper, submerged bedrock platform lies to the south.

Late Pleistocene uplift of marine terraces on the southern Point Reyes peninsula suggests active deformation of offshore structures west of the San Andreas Fault Zone (Grove and others, 2010). The Point Reyes Fault and related structures may be responsible for this recent uplift of the Point Reyes peninsula; however, both the distribution and age control of Pleistocene strata are not well constrained in the Offshore of Point Reyes map area, and, thus, it is difficult to directly link the onshore uplift with the offshore Point Reyes Fault structures. Pervasive stratal thinning within inferred uppermost Pliocene and Pleistocene (that is, post–Purisima Formation) deposits within the anticline that is above the west strand of the Point Reyes Fault Zone (see sheet 8) suggests Quaternary active shortening of the curvilinear, northeast- to north-dipping Point Reyes Fault Zone. Lack of clear deformation in the uppermost Pleistocene and Holocene deposits suggests that activity along the Point Reyes Fault Zone has ceased or slowed since about 21,000 years ago. Although the cumulative, post-Miocene slip rate on the Point Reyes Fault Zone in the map area is poorly constrained, it is estimated to be 0.3 mm/yr on the basis of vertical offset of granitic basement rocks (McCulloch, 1987; Wills and others, 2008).

With the exception of the bathymetric gradient across the Point Reyes Fault, the offshore part of the map area is characterized largely by a relatively flat (less than 0.8°) bedrock platform. The continental shelf is quite wide in this area; the shelf break is located west of the Farallon high (see fig. 1 on sheet 10), about 35 km offshore. Sea level has risen about 125 to 130 m during the last about 21,000 years (see, for example, Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006), 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 dynamic setting and then subjected to Pacific Ocean wave energy and strong currents before deposition or offshore transport.

Much of the inner shelf bedrock platform is composed of Tertiary marine sedimentary rocks, which are underlain by granitic and metamorphic basement rocks of the Salinian block, including the Late Cretaceous Point Reyes Granodiorite porphyritic facies (unit Kgg), which crops out on the seafloor south of the Point Reyes headland. Offshore outcrops of unit Kgg appear to be complexly fractured, similar to onshore exposures, and they have a distinctive massive, bulbous texture that is visible in multibeam imagery. Tertiary strata that overlie the granitic rocks form the core of the Point Reyes Syncline (Weaver, 1949); these strata include the lower Eocene Point Reyes Conglomerate (unit Tpr), the middle and upper Miocene Monterey Formation (unit Tm), the upper Miocene Santa Margarita Sandstone (unit Tsm), and the upper Miocene and Pliocene Purisima Formation (unit Tp). Similarities in age, petrology, petrography, geochemistry, and depositional history indicate that the Point Reyes Conglomerate was deposited in the same submarine canyon system as the Carmelo Formation (Burnham, 2009), mapped about 180 km to the south, and that the two units were subsequently offset along the San Andreas Fault system (Clark and others, 1984; Burnham, 1998; Burnham, 2009). The Point Reyes Conglomerate, whose exposures on the seafloor west of the Point Reyes headland are adjacent to onshore outcrops on the headland, has a relatively massive texture in which few bedding planes are visible, and the strata are highly fractured. On the basis of stratigraphic correlations from both seismic-reflection data and onshore wells, combined with multibeam bathymetry imagery, we infer that rocks of the lower Eocene Point Reyes Conglomerate also extend at least 6 km to the northwest from onshore exposures on the Point Reyes headland. Geologic mapping onshore by Clark and Brabb (1997) indicated that the Santa Cruz Mudstone (unit Tsc) is not present within the onshore Tertiary section in the map area, and it also suggested that the unit is not present within the adjacent offshore stratigraphy either. Data from offshore wells just south of the Point Reyes Fault indicate that a significant amount of the Santa Cruz Mudstone is present within the Tertiary section, suggesting that uplift along the Point Reyes Fault during the late Miocene may explain why no Santa Cruz Mudstone is present directly north of the fault. In the Offshore of Point Reyes map area, the undivided sedimentary rocks unit (Tu) represents seafloor outcrops of a middle Miocene to Pliocene sequence that overlies the Point Reyes Conglomerate (unit Tpr); this undivided unit may include strata of the Monterey Formation (unit Tm), the Santa Margarita Sandstone (unit Tsm), and the Purisima Formation (unit Tp). Seafloor exposures of unit Tu are characterized both by their distinctive rhythmic bedding in which beds are dipping and by a mottled texture in which those beds become flat lying.

Modern nearshore sediments are mostly sand (unit Qms and Qmsw), as well as a mix of sand, gravel, and cobbles (units Qmsc and Qmsd). Coarser grained sands and gravels (units Qmsc and Qmsd) are recognized primarily on the basis of bathymetry and high backscatter (sheets 1, 2, 3). The emergent bedrock platform northwest and west of the Point Reyes headland is heavily scoured, and large areas of unit Qmsc and associated unit Qmsd are present. Both units Qmsc and Qmsd typically have abrupt landward contacts with bedrock, and they form irregular to lenticular exposures. Contacts between units Qmsc and Qms typically are gradational.

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 lack of 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 unit 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.

An area of high backscatter (see sheet 3) and rough seafloor (unit Qsr) is notable in that it includes several small (less than about 20,000 m^2), irregular “lumps” that have as much as 1 m of positive relief above the surrounding seafloor. Southeast of the Point Reyes headland, unit Qsr is mapped in water depths of between 50 and 60 m, and the orientation of the individual lumps ranges from randomly distributed to west trending. Seismic-reflection data (see, for example, fig. 4 on sheet 8) reveal that this lumpy material rests on several meters of uppermost Pleistocene to Holocene sediment and, thus, is not bedrock outcrop. We interpret it as marine debris, possibly derived from the more than 60 shipwrecks that occurred offshore of the Point Reyes peninsula between 1849 and 1940 (National Park Service, 2012). It also is conceivable that this lumpy terrain consists of biological “hardgrounds” (that is, groups of fauna on the seafloor, which have rigid, often calcareous, shells that exhibit high reflectivity, similar to lithified rock). Note that the video ground-truthing data that crosses unit Qsr near the Point Reyes headland (see Box D on sheet 6) was of insufficient quality to distinguish between these two alternatives.

A transition to finer grained marine sediments (unit Qmsf) is seen south of the Point Reyes headland at depths of about 50 to 60 m; however, directly south of Drakes Estero and Estero de Limantour, both backscatter data and seafloor-sediment samples (Chin and others, 1997) suggest that fine-grained sediments extend into water depths as shallow as 30 m. Unit Qmsf, which commonly is extensively bioturbated, primarily consists of mud and muddy sand. These fine-grained sediments are inferred to have been derived either locally from Drakes Estero and Estero de Limantour or from the San Francisco Bay to the south (about 40 km south of the map area) via the predominantly northwestward flow (Noble and Gelfenbaum, 1990). The relative proportions of all offshore map units are shown in table 8–1.

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

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine sedimentary units			
Qms	74,085,785	74.1	39.0
Qmsc	29,268,465	29.3	15.6
Qmsd	10,101,885	10.1	5.4
Qmsf	60,046,614	60.0	32.0
Qmsw	2,500,476	2.5	1.3
Qsr	843,075	0.8	0.4
Total, sedimentary units	176,846,301	176.8	94.1
Marine bedrock and (or) shallow bedrock units			
Tp	5,607,246	5.6	2.9
Tu	5,036,182	5.0	2.7
Tpr	3,953,172	4.0	2.1
Kgg	3,683,591	3.7	2.0
Total, bedrock units	11,004,791	11.0	5.9
Total, Offshore of Point Reyes map area	187,851,092	187.9	100.0

DESCRIPTION OF MAP UNITS

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

Qsr **Marine shelf deposits, rough seafloor (late Holocene)—**Randomly distributed to northwest-trending, irregular “lumps” (as large as 20,000 m^2) that have as much as 1 m of positive relief above seafloor; interpreted as marine debris; possibly related to either one or more shipwrecks or biological “hardgrounds”

Qms **Marine nearshore and shelf deposits (late Holocene)—**Predominantly sand and some mud; ripple marks common; found on gently seaward-dipping (less than 1°) surface between nearshore and water depths of about 30 to 60 m

Qmsc **Coarse-grained marine nearshore and shelf deposits (late Holocene)—**Predominantly coarse sand, gravel, and cobbles; found on gently seaward-dipping (less than 1°) surface in water depths typically less than about 60 m; recognized primarily on basis of high backscatter and flat relief. Extensive exposures (as much as 5 km^2) are mapped on inner shelf north of Point Reyes Fault and near mouth of Drakes Estero and Estero de Limantour where scour (caused by large waves and strong tidal currents in Drakes Bay) has winnowed away fine-grained sediments

Qmsf **Fine-grained marine shelf deposits (late Holocene)—**Predominantly mud, very fine sand, and silt; commonly bioturbated; found on gently seaward-dipping (less than 1°) surface at depths greater than about 30 m offshore of Drakes Estero and Estero de Limantour, as well as at depths greater than about 60 m south and west of Point Reyes headland

Qmsd **Marine shelf scour depressions (late Holocene)—**Inferred to be coarse sand and possibly gravel; consists of irregular, arcuate scour depressions that vary from solitary features occupying 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 Qmsc). Depressions typically are 15 to 50 cm deep, and they have sharp to diffuse boundaries. In map area, both backscatter data and direct camera observations (see, for example, figs. 1, 2 on sheet 4) show small intensity contrasts, suggesting that depressions are filled with sediment that is coarser than intervening elevated sandy shelf deposits; 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

Qmsw **Marine sediment-wave deposits (late Holocene)—**Predominantly sand; formed by strong tidal currents that wrap around Point Reyes headland and into Drakes Bay

Tp **Purisima Formation (Pliocene and late Miocene)—**Siltstone interbedded with mudstone and sandstone; crops out in nearshore and shelf areas in Drakes Bay and also offshore of Point Reyes Beach

Tu **Sedimentary rocks, undivided (Pliocene to middle Miocene)—**May consist of the Monterey Formation (mapped onland as unit Tm), the Santa Margarita Sandstone (mapped onland as unit Tsm), and the Purisima Formation (unit Tp)

Tpr **Point Reyes Conglomerate of Galloway (1977) (early Eocene)—**Marine arkosic sandstone; also includes basal granitic-clast conglomerate that contains distinctive rounded volcaniclastic cobbles; seafloor outcrops appear massive to well bedded

Kgg **Point Reyes Granodiorite, porphyritic facies (Late Cretaceous)—**Contains potassium-feldspar phenocrysts that average 2 to 3 cm in length (maximum, 5 cm); seafloor outcrops appear massive, highly fractured, and bulbous

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Bedrock units compiled from Clark and Brabb (1997) and Wagner and Gutierrez (2010); unit ages, which are from these sources, reflect local stratigraphic relations. Quaternary units compiled from Witter and others (2006) and Wagner and Gutierrez (2010), with some additional mapping by M.W. Manson (this report); in addition, some units modified by M.W. Manson on basis of analysis of 2012 lidar imagery]

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

af **Artificial fill (late Holocene)**—Engineered and (or) nonengineered

afem **Artificial fill over estuarine mud (late Holocene)**—Material deposited by humans over estuarine sediments

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

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

Qa **Alluvial deposits, undivided (late Holocene)**—Fluvial sediment; judged to be latest Holocene age (less than 1,000 years old) on basis of records of historical inundation, identification of youthful meander scars and braid bars on aerial photographs or lidar, or geomorphic position very close in elevation to stream channel

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

Qe **Estuarine deposits (Holocene)**—Heterogeneous mixture of coarse and fine estuarine sediment; deposited in Drakes Estero and Estero de Limantour

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

Qf **Alluvial fan deposits, undivided (Holocene)**—Sediment deposited by streams emanating from mountain canyons onto alluvial valley floors or alluvial plains; may include debris-flow, hyperconcentrated-mudflow, and braided-stream deposits

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

Qls **Landslide deposits (Holocene and Pleistocene)**—Weathered and disintegrated rocks and soil; physically weathered; ranges from deep-seated landslides to active colluvium. Internal contacts differentiate individual landslide bodies

Qmt **Marine-terrace deposits (late Pleistocene)**—Sand, gravel, and cobbles; deposited on marine-abrasion platforms and later uplifted to present-day elevations along coast

Qobs **Older beach-sand deposits (late Pleistocene?)**—Reddish-brown, friable sand and fine gravel

Tp **Purisima Formation (Pliocene and late Miocene)**—Siltstone interbedded with mudstone and sandstone; locally contains diatomite

Tsm **Santa Margarita Sandstone (late Miocene)**—Massive arkosic sandstone

Tm **Monterey Formation (late and middle Miocene)**—Thin-bedded siliceous shale, interbedded with arkosic sandstone

Tl **Laird Sandstone of Clark and others (1984) (late and middle Miocene)**—Arkosic sandstone that contains basal granitic-boulder conglomerate

Tpr **Point Reyes Conglomerate of Galloway (1977) (early Eocene)**—Marine arkosic sandstone; also includes basal granitic-clast conglomerate that contains distinctive rounded volcaniclastic cobbles; seafloor outcrops appear massive to well bedded

Kgg **Point Reyes Granodiorite, porphyritic facies (Late Cretaceous)**—Contains potassium-feldspar phenocrysts that average 2 to 3 cm in length (maximum, 5 cm)

Kgr **Granodiorite and granite of Inverness Ridge (Late Cretaceous)**—Granodiorite and granite; commonly includes aplite and alaskite dikes

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