# California State Waters Map Series—Offshore of Tomales Point, California

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

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

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(Samuel Y. Johnson[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 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.

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This map is part of a series of online U.S. Geological Survey (USGS) publications, each of which includes several map sheets, some explanatory text, and a descriptive pamphlet. Each map sheet is published as a PDF file. Geographic information system (GIS) files that contain both ESRI[6] ArcGIS raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed March 10, 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 Samuel Y. Johnson

The map area offshore of Tomales Point, California, which is referred to herein as the “Offshore of Tomales Point” map area (figs. 1–1, 1–2), is located in northern California, about 60 km north of San Francisco and 110 km south of Point Arena. The map area includes offshore waters, Tomales Point (the north end of the Point Reyes Peninsula), the northern part of Tomales Bay, and coastal lands east of Tomales Bay (fig. 1–2). The onshore part of the map area is largely undeveloped, used primarily for recreation and ranching, as well as oyster farming in Tomales Bay. The Point Reyes Peninsula is part of the Point Reyes National Seashore, and two small areas on the east coast of Tomales Bay are part of the Golden Gate National Recreation Area. The small towns of Tomales and Dillon Beach (populations 204 and 283, respectively, 2010 census) are the largest cultural centers.

Tomales Bay (fig. 1–2), approximately 20-km long and 1- to 2-km wide, formed along a submerged portion of the San Andreas Fault (fig. 1–2), which forms a right-lateral transform boundary between the North American and Pacific tectonic plates. The fault juxtaposes Cretaceous granitic rock to the southwest (exposed on Tomales Point) with the Jurassic and Cretaceous Franciscan Complex to the northeast (exposed on the northeast coast of the Tomales Bay), and has an estimated slip rate of about 17 to 30 mm/yr in this area (Bryant and Lundberg, 2002; Grove and Niemi, 2005). The destructive great 1906 California earthquake (M7.8, 4/18/1906) is thought to have nucleated on the San Andreas Fault about 60 km to the south, offshore of San Francisco (for example, Bolt, 1968; Lomax, 2005), with the rupture extending northward through Tomales Bay and for an additional about 230 km to the south flank of Cape Mendocino.

The northwest coast of Tomales Point is characterized by steep, high (as much as 100 m), barren, granitic cliffs and a rugged shoreline with a few small pocket beaches. Hapke and Reid (2007) documented that as much as 48 m of Tomales Point cliff retreat occurred from 1929–30 to 2002, at rates ranging from about 0.1 to 0.85 m/yr. The granite is in contact with less resistant Tertiary sandstones at Kehoe Beach (fig. 1–2), the northern end of a continuous, wide, sandy beach backed by a large coastal dune field that extends for about 20 km south to Point Reyes Head (fig. 1–1). Hapke and others (2006) indicate that the central about 13 km of the Point Reyes Beach has a long-term (from the middle to late 1800s to 2001) history of accretion, at rates of 0.1 to 1.0 m/yr. Over the short term (1952 to 2001), this beach has a mixed history of accretion and retreat, at rates ranging from -0.7 to 2.0 m/yr (negative numbers indicate beach erosion, positive numbers indicate beach accretion). Both the northern about 2 km and the southern about 5 km of this long beach have mixed to erosional shoreline-change histories. Long-term and short-term change rates in the northern part of the beach range from 0.2 to 0.3 m/yr and -0.1 to -0.9 m/yr, respectively. Long-term and short-term change rates in the southern about 5 km of this long beach range from -0.5 to 0.3 m/yr and -0.1 to -3.0 m/yr, respectively.

Tomales Point relief is asymmetrical so that most small coastal watersheds in the map area drain eastward from Inverness Ridge into Tomales Bay. Many of these steep drainages have small sandy beaches at their mouths. The east coast of Tomales Bay is characterized by more gentle, hummocky, hilly relief underlain by the landslide-prone Franciscan Complex. Keys Creek, the most prominent small watershed entering Tomales Bay from the east, has a small subaqueous delta at its mouth.

Sand Point and Dillon Beach are located at the mouth of Tomales Bay and on the southeasternmost shores of Bodega Bay, respectively (fig. 1–2). The wide beach in this area is backed by an extensive (4.8 $km^2$) sand-dune complex. The enormous volume of sand on the beach and in the dune field is derived from southward littoral drift. This sediment is trapped by Tomales Bay and

Tomales Point, which function as the south end of the Bodega Bay littoral cell (Habel and Armstrong, 1978). Hapke and others (2006) indicate that Dillon Beach has been accreting at rates of 0.1 to 1.8 m/yr over the long term (since the mid to late 1800s) and rates of 0.2 to 2.7 m/yr over the short term (1952 to 2002).

Based on high-resolution bathymetry, sediment sampling, and foraminiferal analyses, Anima and others (2008) divided Tomales Bay into three distinct areas. The Offshore of Tomales Point map area includes all of their Area A at the mouth of Tomales Bay, and the northern part of their Area B in the central bay. Area A is characterized by sand waves, dunes, and flats formed in response to strong tidal flow. In contrast, Area B to the southeast is generally flat and underlain by finer grained sand and silt.

The continental shelf in California's State Waters in the Offshore of Tomales Point map area extends to water depths of about 70 m (mean slope of about 0.7°) and is characterized by extensive, rugged, rocky seafloor. Granitic seafloor has a massive and fractured texture, whereas seafloor sedimentary rock outcrops commonly form distinctive "ribs" created by differential seafloor erosion of dipping beds of variable resistance. Direct sediment supply to this shelf is minimal because littoral drift is blocked to the north by Tomales Bay and Tomales Point, and to the south by the Point Reyes headland.

Potential marine benthic habitats in the Offshore of Tomales Point map area range from unconsolidated continental-shelf sediment, to rocky continental-shelf substrate, to unconsolidated estuary sediments. Rocky-shelf outcrops and rubble are considered to be promising potential habitats for rockfish and lingcod (Cass and others, 1990; Love and others, 2002), both of which are recreationally and commercially important species. Dynamic bedforms, such as the sand waves at the mouth of Tomales Bay, are considered potential foraging habitat for juvenile lingcod and possibly migratory fishes (Beaudreau, 2005), as well as for forage fish such as Pacific sand lance.

Circulation over the continental shelf in the map area (and in the broader northern 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. As a result, net flow over the continental shelf can be more southerly during the spring and summer and more northerly during the fall and winter.

Throughout the year, this part of the central California coast is exposed to four wave climate regimes—the north Pacific swell, the southern swell, northwest wind waves, and local wind waves (Storlazzi and Griggs, 2000; Storlazzi and Wingfield, 2005). The north Pacific swell dominates in winter months (typically November through March), with wave heights at offshore buoys ranging from 2 to 10 m and wave periods ranging from 10 to 25 s (Storlazzi and Wingfield, 2005). During summer months, the largest waves come from the southern swell, generated by storms in the south Pacific and offshore Central America. Characteristically, these swells have smaller wave heights (0.3 to 3 m) and similarly long periods (range 10 to 25 s). Northwest wind waves affect the coast throughout the year, while local wind waves are most common from October to April. These two wind-wave regimes typically have wave heights of 1 to 4 m and short periods (3 to 10 s).

## Publication Summary

This publication about the Offshore of Tomales Point map area includes ten map sheets that contain explanatory text, in addition to this descriptive pamphlet, and a data catalog of geographic information system (GIS) files. Sheets 1, 2, and 3 combine data from 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 prominent, massive to ribbed outcrops of granitic and sedimentary rocks, and flat, sediment-covered seafloor offshore of Tomales Point and in Tomales Bay. To validate geological and biological interpretations of the sonar data shown in sheets 1, 2, and 3, the U.S. Geological Survey towed a camera sled over specific offshore locations, collecting both video and photographic imagery; this "ground-truth" surveying data is summarized on sheet 6. Sheet 5 is a "seafloor character" map, which classifies the seafloor on the basis of depth, slope, rugosity (ruggedness), and backscatter intensity and which is further informed by the ground-truth-survey imagery. Sheet 7 is a map of "potential habitats," which are delineated on the basis of substrate type, geomorphology, seafloor process, or other attributes that may provide a habitat for a specific species or assemblage of organisms. Sheet 8 compiles representative seismic-reflection profiles from the map area, providing information on the subsurface stratigraphy and structure of the map area. Sheet 9 shows the distribution and thickness of young sediment (deposited over the last about 21,000 years, during the most recent sea-level rise), in both the map area and the larger offshore Salt Point to Drakes Bay region, interpreted on the basis of the seismic-reflection data, and it identifies the Offshore of Tomales Point map area as lying within in the Bodega-Tomales shelf domain. 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), high-resolution seismic-reflection profiles (sheet 8), and air-photo interpretation of the nearshore.

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.

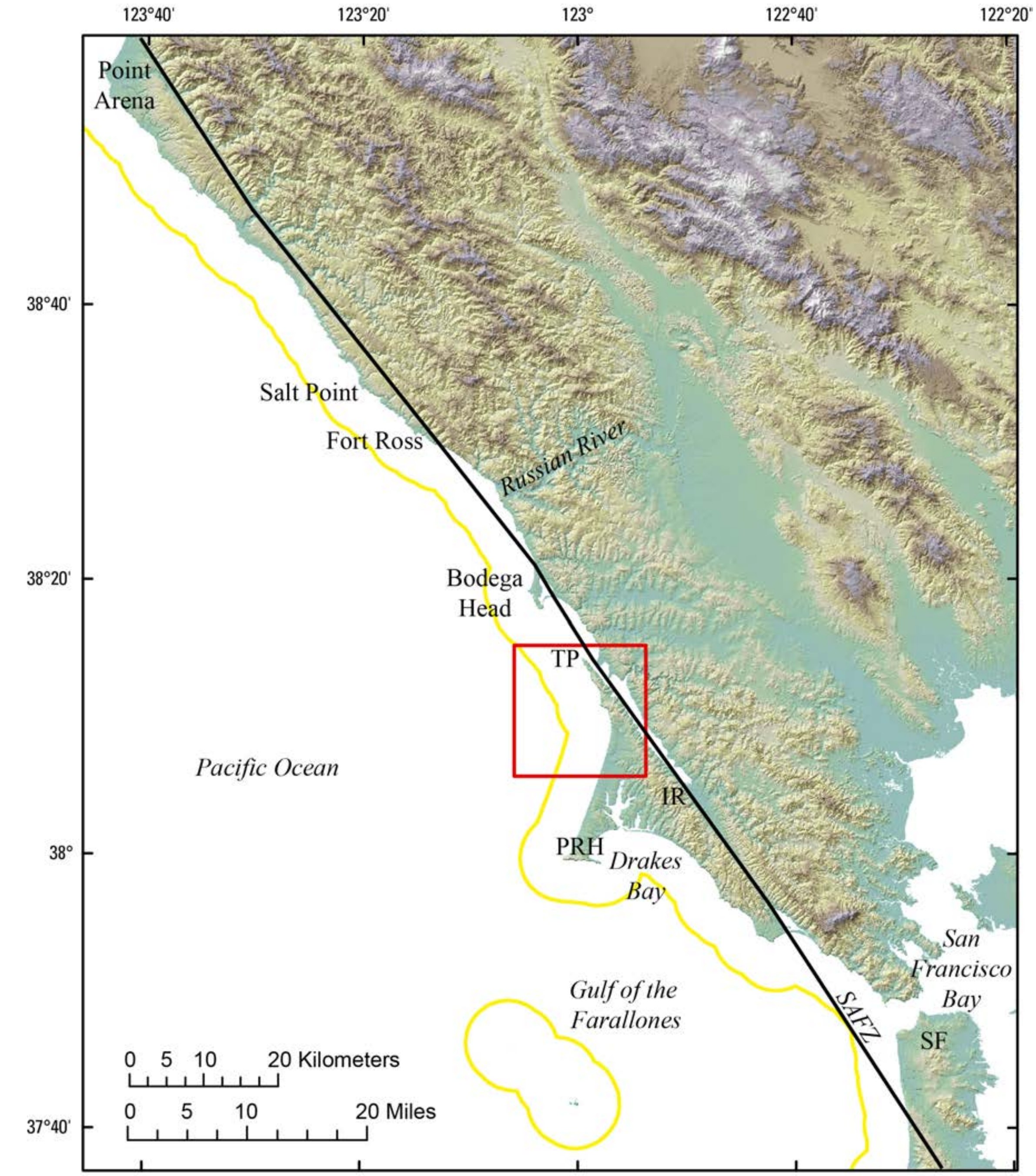


**Figure 1–1.** Physiography of northern California coast from Point Arena to San Francisco (SF). Red box shows Offshore of Tomales Point map area. Yellow line shows limit of California's State Waters. Other abbreviations: IR, Inverness Ridge; PRH, Point Reyes headland; SAFZ, San Andreas Fault Zone;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

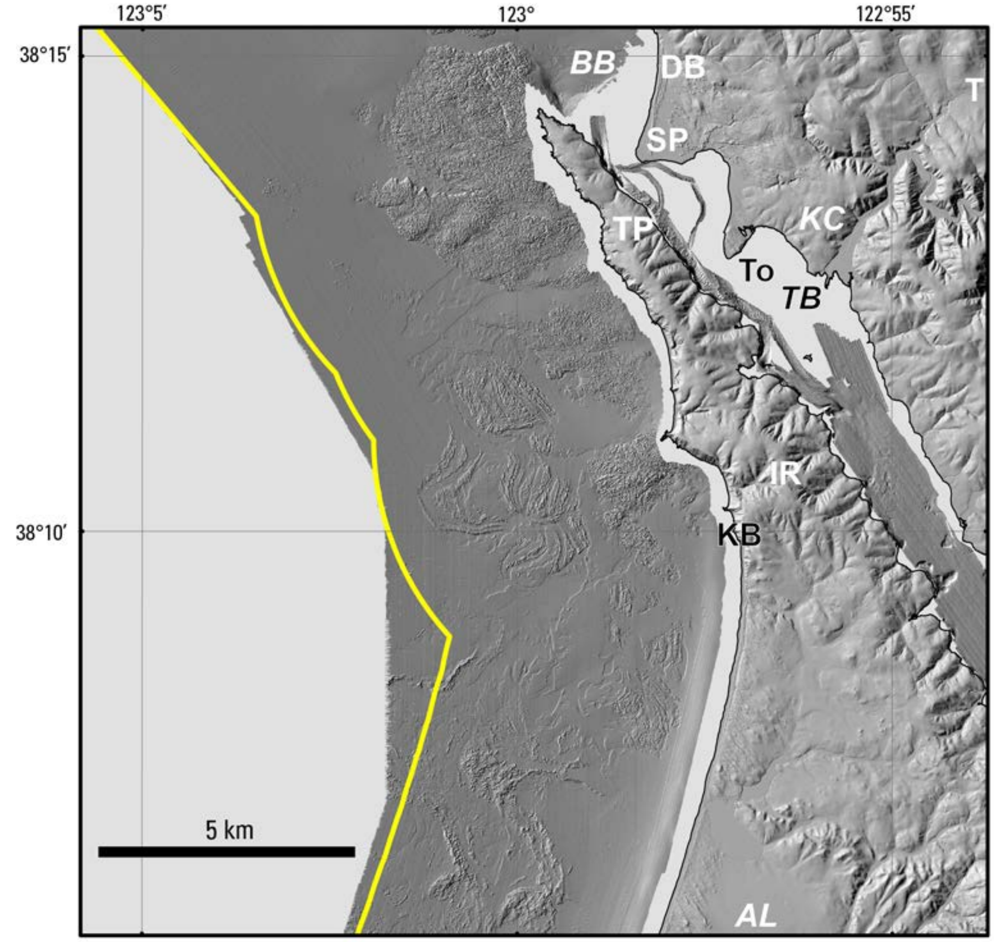


Figure 1–2. Coastal geography of Offshore of Tomales Point map area. Yellow line shows limit of California's State Waters. Abbreviations: AL, Abbots Lagoon; BB, southernmost Bodega Bay; DB, Dillon Beach; IR, Inverness Ridge; KB, Kehoe Beach; KC, Keys Creek; SP, Sand Point; T, Tomales; To, Toms Point; TP, Tomales Point.

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

By Peter Dartnell and Rikk G. Kvitek

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of Tomales Point map area in northern California were generated from bathymetry and backscatter data collected by Fugro Pelagos, by California State University, Monterey Bay (CSUMB), and by the U.S. Geological Survey (USGS). Mapping was completed between 2004 and 2010, using a combination of 200-kHz and 400-kHz Reson 7125 and 244-kHz Reson 8101 multibeam echosounders, as well as 234-kHz and 468-kHz SEA SWATHplus bathymetric sidescan-sonar systems. These mapping missions combined to collect both bathymetry (sheets 1, 2) and acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 3-nautical-mile limit of California's State Waters.

During the Fugro Pelagos and CSUMB mapping missions, an Applanix POS MV (Position and Orientation System for Marine Vessels) was used to accurately position the vessels during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm). To account for tidal-cycle fluctuations, 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 Geocoder within Caris HIPS and SIPS 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 together into 1- or 2-m-resolution images. Overlap between parallel lines was resolved using a priority table whose values were based on the distance of each sample from the ship track, with the samples that were closest to and furthest from the ship track being given the lowest priority. An anti-aliasing algorithm was also applied. The mosaics were then exported as georeferenced TIFF images, imported into a geographic information system (GIS), and converted to GRIDs at 2-m resolution.

During the USGS mapping mission within Tomales Bay (Anima and others, 2008), differential GPS (DGPS) data were combined with measurements of vessel motion (heave, pitch, and roll) in a CodaOctopus F180 attitude-and-position system to produce a high-precision vessel-attitude packet. This packet was transmitted to the acquisition software in real time and combined with instantaneous sound-velocity measurements at the transducer head before each ping. The returned samples were projected to the seafloor using a ray-tracing algorithm that works with previously measured sound-velocity profiles. Statistical filters were applied to the raw samples that discriminate the seafloor returns (soundings) from unintended targets in the water column. Finally, the soundings were converted into 2-m-resolution bathymetric-surface-model grids. The backscatter data were postprocessed using USGS software (D.P. Finlayson, written commun., 2011) that normalizes for time-varying signal loss and beam-directivity differences. Thus, the raw 16-bit backscatter data were gain-normalized to enhance the backscatter of the SWATHplus system. The resulting normalized-amplitude values were rescaled to 16-bit and gridded into GeoJPEGs using GRID Processor Software, then imported into a GIS and converted to GRIDs.

Processed soundings from the different mapping missions were exported from the acquisition or processing software as XYZ files and bathymetric surfaces. All 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 greens to represent greater depths (note that the Offshore of Tomales Point map area requires only the shallower part of the full-rainbow color ramp used on some of the other maps in the California State Waters Map Series; see, for example, Kvitek and others, 2012). This colored bathymetry surface was draped over the shaded-relief imagery at 60-percent transparency to create a colored shaded-relief map (sheet 1). Note that the ripple patterns and 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, 7, and 10) were generated at 10-m intervals from a modified 2-m-resolution bathymetric surface. The original surface was smoothed using the Focal Mean tool in ArcGIS and a circular neighborhood with a radius of 20 to 30 m (depending on the area). The contours were generated from this smoothed surface using the ArcGIS Spatial Analyst Contour tool. The most continuous contour segments were preserved; smaller segments and isolated island polygons were excluded from the final output. Contours were smoothed using a polynomial approximation with exponential kernel algorithm and a tolerance value of 60 m.

The 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 an 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 onshore-area image was generated by applying an illumination having an azimuth of 300° and from 45° above the horizon to 2- and 3-m-resolution topographic-lidar data available from 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 Tomales Point Map Area (Sheet 4)

By Peter Dartnell

Mapping California's State Waters has produced a vast amount of acoustic and visual data, including bathymetry, acoustic backscatter, seismic-reflection profiles, and seafloor video and photography. Researchers use these data to develop maps, reports, and other tools to assist coastal-zone managers and other stakeholders in coastal and marine spatial-planning. For example, seafloor-character (sheet 5), habitat (sheet 7), and geologic (sheet 10) maps of the Offshore of Tomales Point map area may assist in the designation of Marine Protected Areas, as well as in their monitoring. These maps and reports also help to analyze environmental change owing to sea-level rise and coastal development, to model and predict sediment and contaminant budgets and transport, to site offshore infrastructure, and to assess tsunami and earthquake hazards. To facilitate this increased understanding and to assist in product development, it is helpful to integrate the different datasets and then view the results in three-dimensional representations such as those displayed on the data integration and visualization sheet for the Offshore of Tomales Point map area (sheet 4).

The maps and three-dimensional views on sheet 4 were created using a series of geographic information systems (GIS) and visualization techniques. Using GIS, the bathymetric and topographic data (sheet 1) were converted to ASCIIRASTER format files, and the acoustic-backscatter data (sheet 3) were converted to geoTIFF images. The bathymetric and topographic data were imported in the Fledermaus® software (QPS). The bathymetry was color-coded to closely match the colored shaded-relief bathymetry on sheet 1 in which reds 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 Tomales Point map area, which includes outcrops of fractured bedrock and complex patterns of shallow depressions.

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

Block diagrams that combine the bathymetry and backscatter 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 Tomales Point Map Area (Sheet 5)

By Mercedes D. Erdey and Guy R. Cochrane

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

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

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

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

The seafloor-character map of the Offshore of Tomales Point map area (sheet 5) was produced using video-supervised maximum-likelihood classification of the bathymetry and intensity of return from sonar systems, following the method described by Cochrane (2008). The two variants used in this classification were backscatter intensity and derivative rugosity. 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 Tomales Point map area, only Depth Zones 2 and 3 are present. The slope classes that represent the CMECS slope zones are Slope Class 1 = flat (0° to 5°), Slope Class 2 = sloping (5° to 30°), Slope Class 3 = steeply sloping (30° to 60°), Slope Class 4 = vertical (60° to 90°), and Slope Class 5 = overhang (greater than 90°); in the Offshore Tomales Point map area, only Slope Classes 1 and 2 are present. The final classified seafloor-character raster map image has been draped over the shaded-relief bathymetry for the area (sheets 1 and 2) to produce the image shown on the seafloor-character map on sheet 5.

The seafloor-character classification also is summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 56.5 percent (71.7 $km^2$) of the map area: 14.3 percent (18.2 $km^2$) is in Depth Zone 2, and 42.2 percent (53.5 $km^2$) 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 23.9 percent (30.2 $km^2$) of the map area: 4.2 percent (5.3 $km^2$) is in Depth Zone 2, and 19.7 percent (24.9 $km^2$) is in Depth Zone 3. Rock and boulder, rugose (rock and boulder outcrops having high surficial complexity) makes up 14.4 percent (18.2 $km^2$) of the map area: 6.9 percent (8.7 $km^2$) is in Depth Zone 2, and 7.5 percent (9.5 $km^2$) 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 5.2 percent (6.6 $km^2$) of the map area: 0.8 percent (1.0 $km^{2)}$ is in Depth Zone 2 and 4.4 percent (5.6 $km^2$) is in Depth Zone 3.

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

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

The seafloor in the Offshore of Tomales Point map area is complex, dominated by fractured and folded, rugose bedrock outcrops (Class III). 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) have also been identified adjacent to rock outcrops. The Tomales Bay inlet is dominated by Class I sediments of sand and mud and large sandwaves formed by coarser sand (Class IV).

Due to the mixture of different sediments covering the seafloor within this map area, the classification accuracy is found to be somewhat lower than for other areas we have mapped in California's State Waters, as determined by comparing the shipboard video observations and the classified map—53 percent accurate for Class I, 49 percent accurate for Class II, 38 percent accurate for Class III, and 46 percent accurate for Class IV. Coarser sediments accumulated in seafloor depressions (Class IV) often form megaripples, which might not be always recognizable on the video footage especially when visibility is limited. 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. The lower classification accuracy in all classes is likely due to the relatively narrow and intermittent nature of transition zones (from fine to coarse sediment to rock), relative to the observation buffer size. A single buffered observation locale of 78 pixels, therefore, is likely to be interspersed with other classes of pixels, in addition to Class III. Percentages for presence/absence within a buffer also were calculated as a better measure of the accuracy of the classification for patchy rock habitat. The presence/absence accuracy was found to be significant for all classes (76 percent for Class I, 76 percent for Class II, 76 percent for Class III, and 55 percent for Class IV).

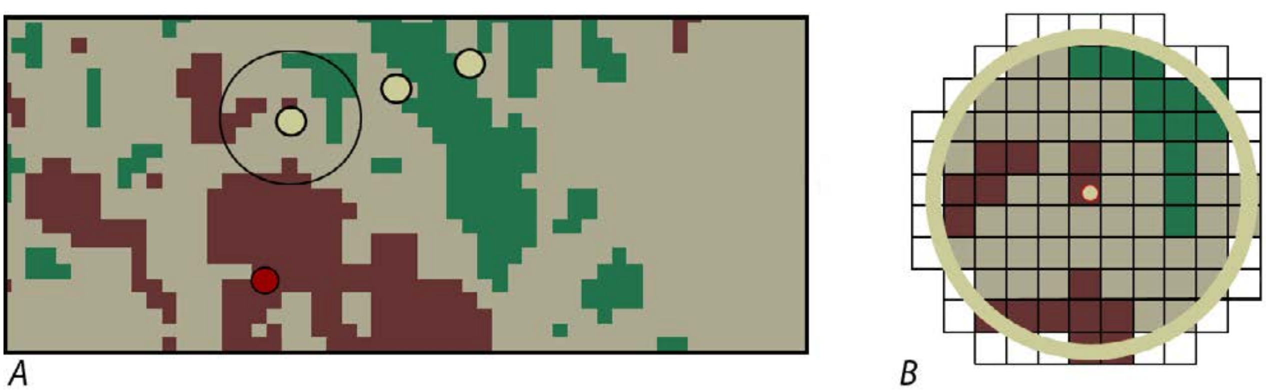


Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

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

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

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

| Primary-substrate component | Secondary-substrate component | Abiotic seafloor complexity | Low-visibility observations |
|---|---|---|---|
| cobbles | sand | moderate | |
| mud | boulders | moderate | |
| sand | boulders | moderate | |
| rock | boulders | moderate | |
| rock | boulders | high | |
| rock | cobbles | moderate | |
| rock | mud | moderate | |
| rock | rock | moderate | |
| rock | rock | high | |
| rock | sand | moderate | |
| rock | sand | high | |
| Class IV | | | |
| sand | sand | low | |
| sand | sand | moderate | |
| | | | megaripples |
| | | | oscillatory megaripples |
| | | | depression |

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

[Accuracy assessments are based on video observations]

| Class | Number of observations | % majority | % presence/absence |
|---|---|---|---|
| I—Fine- to medium-grained smooth sediment | 216 | 53.4 | 76.4 |
| II—Mixed smooth sediment and rock | 172 | 49.0 | 76.2 |
| III—Rock and boulder, rugose | 239 | 38.0 | 76.2 |
| IV—Medium- to coarse-grained sediment (in scour depressions) | 42 | 45.8 | 54.8 |

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

By Nadine E. Golden and Guy R. Cochrane

To validate the interpretations of sonar data in order to turn it into geologically and biologically useful information, the U.S. Geological Survey (USGS) towed a camera sled (fig. 5–1) over specific locations throughout the Offshore of Tomales Point map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred in 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 11 trackline kilometers of video and 547 still photographs, in addition to 731 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.


Figure 5–1. Photograph of camera sled used in USGS 2008 ground-truth survey.

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

The camera-sled tracklines (shown by colored dots on the map on sheet 6) are sited in order to visually inspect areas representative of the full range of bottom hardness and rugosity in the map area. The video is fed in real time to the research vessel, where USGS and National Oceanic and Atmospheric Administration (NOAA) scientists record both the geologic and biologic character of the seafloor. While the camera is deployed, several different observations are recorded for a 10-second period once every minute, using the protocol of Anderson and others (2007). Observations of primary substrate, secondary 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 C); 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 Tomales Point map area, the seafloor surface is characterized by patchy distributions of sandy sediment and exposed rock. Nearshore areas of rocky habitat are notably present along the wave-exposed coast of Tomales Point in the northern half of the map area. Rocks exposed in this area (sheet 6 on fig. 1J) are massive granitic rocks uplifted along the San Andreas Fault (see also, sheet 10). To the south, exposures of layered-sedimentary rock in deeper water are of lower relief, consisting of both Class II (fig. 3E on sheet 6) and Class III (fig. 3H on sheet 6) habitat types, indicating differential erosion of less resistant layers. The patchy combination of different geologic units across the spectrum of depths makes this one of the more diverse habitat areas.

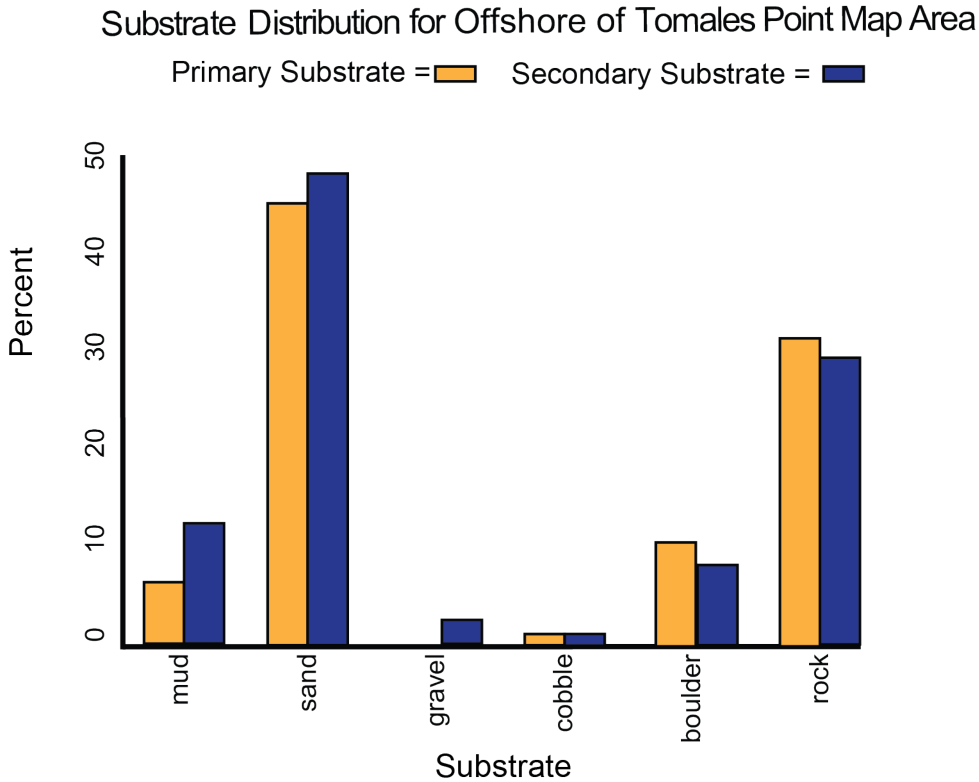


Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Tomales Point map area.

# Chapter 6. Potential Marine Benthic Habitats of the Offshore of Tomales Point 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 Tomales Point map area, representing a substrate type, geomorphology, seafloor process, or any other attribute that may provide a habitat for a specific species or assemblage of organisms. This map, which is based largely on seafloor geology, also integrates information displayed on several other thematic maps of the Offshore of Tomales Point map area. High-resolution sonar bathymetry data, converted to depth grids (seafloor DEMs; sheet 1), are essential to development of the potential marine benthic habitat map, as is shaded-relief imagery (sheet 2), which allows visualization of seafloor terrain and provides a foundation for interpretation of submarine landforms.

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

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

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

## Classifying Potential Marine Benthic Habitats

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

The four categories and their attribute codes that are used on the Offshore of Tomales Point 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 = Ripples, 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 Tomales Point map area are 23 potential marine benthic habitat types, covering 126.97 $km^2$. These include unconsolidated sediments, mixed substrate, hard substrate, and possible anthropogenic features on the continental shelf, as well as unconsolidated sediments and mixed substrate in the estuary. The habitat types mapped on the shelf cover an area of 117.22 $km^2$ (92.3 percent) while those in the estuary (Tomales Bay) cover 9.75 $km^2$ (7.7 percent). In the total area mapped (shelf and estuary), the predominant habitat type is soft unconsolidated sediment, covering 85.30 $km^2$ (67.2 percent). Exposed hard bedrock covers 37.34 $km^2$ (29.4 percent); sediment-covered bedrock, which is of the mixed hard-soft induration class, covers 4.21 $km^2$ (3.3 percent); hard, unidentified anthropogenic features, possibly related to marine debris, covers 0.13 $km^2$ (0.1 percent).

Rock outcrops and rubble are considered the primary habitat types for rockfish and lingcod (Cass and others, 1990; Love and others, 2002), both of which are recreationally and commercially important species. Dynamic bedforms such as sand waves are considered potential foraging habitat for juvenile lingcod (*Ophiodon elongatus*) and possibly migratory fishes (Beaudreau, 2005), as well as for forage fish such as Pacific sand lance.

# Chapter 7. Subsurface Geology and Structure of the Offshore of Tomales Point Map Area and the Salt Point to Drakes Bay Region (Sheets 8 and 9)

By Samuel Y. Johnson, Stephen R. Hartwell, Janet T. Watt, Ray W. Sliter, and John L. Chin

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 Tomales Point map area. These data, which are collected at two 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, 4, 6, and 7) 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). These high-resolution data can resolve geologic features that are a few meters thick (small-scale features) to subbottom depths of as much as a few hundred meters.

Figure 5 on sheet 8 shows a deep-penetration, migrated, multichannel seismic-reflection profile collected in 1976 by WesternGeco on cruise W–14–76–SF. This profile and other similar data were collected in many areas offshore of California in the 1970s and 1980s when these areas were considered a frontier for oil and gas exploration. 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 using 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 Tomales Point map area. The northwest-trending San Andreas Fault strikes through Tomales Bay in the northeastern part of the map area. Fault slip along the San Andreas Fault has uplifted Cretaceous granitic rock and overlying folded, Neogene marine sedimentary forming Tomales Point and much of the rugged, rocky, continental shelf on its west flank. These two different rock types are mapped on the seafloor (sheet 10) based on their distinctive surface morphology. Granitic seafloor outcrops are characterized by a massive hackly texture and are cut by dense networks of crosscutting fractures and small faults. In contrast, folded Neogene sedimentary rocks are characterized by a "ribbed" seafloor morphology, which results from dipping beds (lithologies) having variable resistance to erosion. In the southern part of the map area offshore of Abbots Lagoon (fig. 1–2), sedimentary rocks are less "ribbed," owing to shallower dips and more uniform lithologies (sheet 10). Seafloor underlain by granitic rocks typically slopes more than 1°, whereas the seafloor underlain by sedimentary rocks slopes about 0.5°.

On seismic-reflection data, the granitic rocks are notably "reflection-free," whereas the sedimentary rocks are characterized by continuous, parallel to subparallel, variable amplitude, high-frequency reflections (terminology after Mitchum and others, 1977). Within the sedimentary rocks, intrastratal low-angle unconformities and broad (as wide as about 1 km) channels are common (for example, figs. 3, 4, 6 on sheet 8). Lenses of chaotic reflections (for example, figs. 3, 4 on sheet 8) primarily consist of the internally deformed fill of small-scale channels.

Surficial and shallow sediments were deposited in the last about 21,000 years during the sea-level rise that followed the Last Glacial Maximum (LGM) and the last major lowstand (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006). Sea level was about 125 m lower during the LGM, at which time the Offshore of Tomales Point map area was emergent, and the shoreline was about 30 km west of its present location. 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). Sea-level rise led to broadening of the continental shelf, progressive eastward migration of the shoreline and wave-cut platform, and associated transgressive erosion and deposition.

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, 4, 6) and their thickness is shown on sheet 9 (Maps B, D). The contact between underlying granitic and sedimentary bedrock and post-LGM sediment is an abrupt transgressive surface of erosion (see, for example, Catuneanu, 2006), commonly marked by minor channeling, and a common upward change to lower amplitude, more diffuse reflections.

## Geologic Structure and Recent Deformation

Faults in the offshore part of the 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. Most of the map area lies southwest of the right-lateral San Andreas Fault Zone, a transform boundary between the North American and Pacific tectonic plates. The San Andreas Fault strikes through Tomales Bay (sheet 10), and only the western part of the zone is imaged on one seismic-reflection profile in the map area (sheet 8, fig. 1); the profile reveals a down-dropped sedimentary basin in the fault zone, bounded to the west by uplifted granitic rocks. Nearby, onland geologic studies along this section of the San Andreas Fault suggest a slip rate of 17 to 30 mm/yr (Bryant and Lundberg, 2002; Grove and Niemi, 2005).

Both the high-resolution bathymetry (sheets 1, 2) and the seismic-reflection data (sheet 8) reveal complex structure beneath the bedrock shelf west of Tomales Point. Numerous northwest-striking faults cut both granitic and sedimentary rocks, and their depositional contacts (sheet 8, figs. 1, 6; sheet 10). Folds axes trend west to northwest and folds have common wavelengths of 0.5 to 2 kilometers. The folding occurred during the late Pliocene or Pleistocene; it does not obviously involve post-LGM sediments, and the upper Miocene and Pliocene Purisima Formation is apparently the youngest folded unit (Clark and Brabb, 1997). Folding may be synchronous with activity on the northwest-trending Point Reyes Thrust Fault which lies about 16 km offshore of the map area (McCulloch, 1987; Heck and others, 1990; also see sheet 10, fig. 1).

Map E on sheet 9 shows the regional pattern of major faults and earthquakes. Fault location is simplified and compiled from our mapping within California's State Waters (see sheet 10), McCulloch (1987), 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 (M2.1, 11/18/1978) was located about 5 km west of the Point Reyes Peninsula. 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 60 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 Tomales Point 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 minor 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 post-LGM unit in the Offshore of Tomales Point map area ranges from 0 to 11 m (Map B on sheet 9), and the depth to the base of this unit ranges from about 10 m to 85 m (Map A on sheet 9). Mean sediment thickness for the map area is 2.3 m and the total sediment volume is $253 \times 10^6$ $m^3$ (table 7–1). The thickest sediment occurs along the northern map boundary, at the mouth of Tomales Bay, and at water depths of about 60 to 75 m due west of Tomales Point. These two areas were once connected as upper and lower reaches of a now-submerged channel system which provided an outlet for local coastal drainages, including what is now Tomales Bay.

To the south, Cretaceous granitic and Tertiary sedimentary rock crop out on the seafloor or are buried by only a thin cover (mostly less than 2.5 m) of uppermost Pleistocene and Holocene sediment. This thin sediment cover, in part, results from limited sediment supply. Tomales Point blocks southward littoral drift and west-facing coastal watersheds on this part of the Point Reyes Peninsula are very small; therefore, much of the relatively meager sediment that is present on the shelf could be derived from erosion of local coastal bluffs and sand dunes. The continental shelf offshore of Tomales Point is also subject to high wave energy, which has the potential to rework and transport sediment off the shallow to midshelf into deeper water.

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, is the largest sediment source on this part of the coast and has the thickest uppermost Pleistocene and Holocene sediment in the region (mean thickness, 21.1 m). The northward extension of this domain 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 (including most of the Drakes Bay and Vicinity map area), 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 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 Tomales Point 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 Tomales Point map area | | | |
| Offshore of Tomales Point map area | 111 | 2.3 | 253 |

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

By Samuel Y. Johnson, Michael W. Manson, Stephen R. Hartwell, and H. Gary Greene

## Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Tomales Point map area from approximate Mean High Water (MHW) to the 3-nautical-mile limit of California's State Waters. MHW is defined at an elevation of 1.46 m above the North American Vertical Datum of 1988 (NAVD 88) (Weber and others, 2005). Offshore geologic units were delineated on the basis of integrated analyses of adjacent onshore geology with multibeam bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8). Aerial photographs taken in multiple years were used to map the nearshore area (0 to 10 m water depth) and to link the offshore and onshore geology.

Onshore bedrock mapping is compiled from Galloway (1977), Clark and Brabb (1997), and Wagner and Gutierrez (2010). 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. Traces of the San Andreas Fault are compiled from California Geological Survey (1974).

The morphology and the geology of the offshore part of the Offshore of Tomales Point map area result from the interplay between tectonics, sea-level rise, local sedimentary processes, and oceanography. The map area is cut by the northwest-striking San Andreas Fault, a right-lateral transform boundary between the North American and Pacific tectonic plates. The San Andreas Fault strikes through Tomales Bay, the northern part of a linear valley that extends from Bolinas through Olema Valley to Bodega Bay, which separates mainland California from the Point Reyes Peninsula (fig. 1–1). Onshore investigations indicate that this section of the San Andreas Fault has an estimated slip rate of about 17 to 25 mm/yr (Bryant and Lundberg, 2002; Grove and Niemi, 2005). The devastating great 1906 California earthquake (M7.8, 4/18/1906) is thought to have nucleated on the San Andreas Fault about 60 km south of this map area offshore of San Francisco (for example, Bolt, 1968; Lomax, 2005), with the rupture extending northward through the Offshore of Tomales Point map area to the south flank of Cape Mendocino (Lawson, 1908; Brown and Wolfe, 1972).

The Point Reyes Peninsula is bounded to the south and west in the offshore by the north- and east-dipping Point Reyes Thrust Fault (McCulloch, 1987; Heck and others, 1990; also see fig. 1 on sheet 10), which lies about 20 km west of Tomales Point. Granitic basement rocks are offset about 1.4 km on this thrust fault offshore of Point Reyes (McCulloch, 1987), and this uplift combined with west-side-up offset on the San Andreas Fault (Grove and Niemi, 2005) resulted in uplift of the Point Reyes Peninsula, including Tomales Point and the adjacent continental shelf. Grove and others (2010) reported uplift rates of as much as 1 mm/yr for the south flank of the Point Reyes Peninsula based on marine terraces, but reported no datable terrace surfaces that could constrain uplift for the flight of 4–5 terraces exposed farther north along Tomales Point.

Because of this Quaternary uplift and relative lack of sediment supply from coastal watersheds, there is extensive rugged, rocky seafloor beneath the continental shelf in the Offshore of Tomales Point map area. Granitic rocks (unit Kg) on the seafloor are mapped on the basis of massive character, roughness, extensive fractures, and high backscatter (sheet 3). Neogene sedimentary rocks (units Tl and

Tu) commonly form distinctive “ribs,” created by differential seafloor erosion of dipping beds of variable resistance. The more massive offshore outcrops of unit Tu in the southern part of the map area are inferred to represent more uniform lithologies. Slopes on the granitic seafloor (generally 1° to 1.3°) are greater than those over sedimentary rock (generally about 0.5° to 0.6°).

Sediment-covered areas occur in gently sloping (less than about 0.6°) midshelf environments west and north of Tomales Point, and at the mouth of Tomales Bay. Sediment supply is local, limited to erosion from local coastal bluffs and dunes, small coastal watersheds, and sediment flux out of the mouth of Tomales Bay. Shelf morphology and evolution largely reflects eustacy; sea level has risen about 125 to 130 m over about the last 21,000 years (for example, Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006), leading to broadening of the continental shelf, progressive eastward migration of the shoreline and wave-cut platform, and associated transgressive erosion and deposition.

Given present exposure to high wave energy, modern nearshore to midshelf sediments are mostly sand (unit Qms) and a mix of sand, gravel, and cobbles (units Qmsc and Qmsd). These sediments are distributed between rocky outcrops at water depths of as much as 65 m (see below). Coarser grained sands and gravels (units Qmsc and Qmsd) are recognized primarily on the basis of bathymetry and high backscatter (sheets 1, 2, 3).

Unit Qmsd typically is mapped as erosional lags in scour depressions (see, for example, Cacchione and others, 1984) that are bounded by relatively sharp contacts with bedrock, or sharp to diffuse contacts with units Qms and Qmsc. These depressions typically are a few tens of centimeters deep and range in area from a few tens of square meters to more than one square kilometer. 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 (thus 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 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.

Unit Qmsf consists primarily of mud and muddy sand and is commonly extensively bioturbated. The location of the inboard contact at water depths of about 65 m is based on meager sediment sampling and photographic data (sheets 5, 6) and the inference that it must lie offshore of the outer boundary of coarse-grained units Qmsd and Qmsc. This is notably deeper than the inner contact of unit Qmsf offshore of the nearby Russian River (about 50 m; Klise, 1984), which result from both increased wave energy and significantly decreased supply of muddy sediment.

Two areas of high-backscatter (see sheet 3) and rough seafloor (unit [illegible]) are notable in that each includes several small (less than about 20,000 $m^2$), irregular “mounds” that have as much as 1 m of positive relief above the surrounding seafloor. West of northern Tomales Point, unit [illegible] is mapped in water depths of between 65 and 70 m, and the orientation of the individual mounds ranges from randomly distributed to northwest-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 think this material is most likely 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 with rigid, often calcareous, shells that exhibit high reflectivity, similar to lithified rock).

Units Qsw, Qstb, Qdtb, and Qkdtb comprise sediments in Tomales Bay. Anima and others (2008) conducted a high-resolution bathymetric survey of Tomales Bay and noted that strong tidal currents at the mouth of the bay had created a large field of sandwaves, dunes, and flats (unit Qsw). Unit Qkdtb is a small subaqueous sandy delta deposited at the mouth of Keys Creek, the largest coastal watershed draining into this northern part of Tomales Bay. Unit Qstb occurs south of units Qsw and Qdtb, and comprises largely flat seafloor underlain by mixed sand and silt. Unit Qdtb consists of depressions within the sedimentary fill of Tomales Bay. These depressions commonly occur directly offshore of coastal promontories, cover as much as 74,000 $m^2$, and are as deep as 9 m. 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 Tomales Point map area.

| Map Unit | Area ($m^2$) | Area ($km^2$) | Percent of total area |
|---|---|---|---|
| Marine sedimentary units | | | |
| Qmsr | 121,009 | 0.1 | 0.1 |
| Qms | 39,278,404 | 39.3 | 31.4 |
| Qmsc | 5,606,064 | 5.6 | 4.5 |
| Qmsf | 31,709,349 | 31.7 | 25.4 |
| Qmsd | 7,141,722 | 7.1 | 5.7 |
| Total, sedimentary units | 83,856,547 | 83.9 | 67.1 |
| | | | |
| Marine bedrock and (or) shallow bedrock units | | | |
| Tu | 18,014,905 | 18.0 | 14.4 |
| Tl | 382,910 | 0.4 | 0.3 |
| Kg | 22,804,258 | 22.8 | 18.2 |
| Total, bedrock units | 41,202,073 | 41.2 | 32.9 |
| Total, California’s State Waters | 125,058,620 | 125.1 | 100.0 |
| | | | |
| Tomales Bay units | | | |
| Qsw | 7,077,418 | 7.1 | 39.7 |
| Qstb | 9,226,965 | 9.2 | 51.7 |
| Qkdtb | 1,370,212 | 1.4 | 7.7 |
| Qdtb | 155,368 | 0.2 | 0.9 |
| Total, Tomales Bay map area | 17,829,963 | 17.8 | 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 "mounds" (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)—**Mostly sand; ripple marks common; found on gently seaward-dipping (less than 1°) surface between nearshore and water depths of about 65 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 up to 65 m; recognized primarily on basis of high backscatter and flat relief

Qmsf **Fine-grained marine shelf deposits (late Holocene)—**Predominantly mud, very fine sand, and silt; commonly bioturbated; found on gently seaward-dipping (less than 1°) surfaces at depths greater than about 65 m

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 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

Qstb **Sediments of central Tomales Bay (late Holocene)—**Mixed fine sand and silt on the mostly flat floor of Tomales Bay. Anima and others (2008) report that sediment in the south-central part of the bay is fine sand to coarse silt; they sampled fine to very fine sand at the mouths of several small coastal watersheds

Qsw **Sand at the mouth of Tomales Bay (late Holocene)—**Anima and others (2008) report that coarse to medium sand is present at the mouth of Tomales bay, forming a large field of sand waves, dunes, and flats

Qkdtb **Subaqueous delta at the mouth of Walker Creek (late Holocene)—**Semicircular subaqueous delta extending into Tomales Bay from the mouth of Walker Creek

Qdtb **Seafloor depressions in Tomales Bay (late Holocene)—**Oval to oblate depressions within the sedimentary fill of Tomales Bay. Individual depressions are as much as 74,000 $m^2$ in area and are as much as 9 m deep

Tu **Sedimentary rocks, undivided (late Pliocene to middle Miocene)—**Consists of Laird Sandstone (unit Tl), Monterey Formation (unit Tm), Santa Margarita Sandstone (unit Tsm), and Purisima Formation (unit Tp) (see below); units decrease in age to the southwest

Tl **Laird Sandstone (middle Miocene)**—Marine arkosic sandstone, includes basal granitic conglomerate

Kg **Granitic rocks (Cretaceous)**—Offshore equivalent of the tonalite of Tomales Point (unit Kgd) and the Granodiorite and granite of Inverness Ridge (unit Kgr) (Clark and Brabb, 1997); mapped based on high backscatter and rough, massive, fractured, seafloor morphology

## ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units are compiled from Clark and Brabb (1997), Witter and others (2006), and Wagner and Gutierrez (2010)]

af **Artificial fill (late Holocene)**—Material placed by humans

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 for the purpose of containing flood or tidal waters

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

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

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

Qt **Stream terrace deposits (late Holocene)**—Stream terrace deposits judged to be late Holocene (<1,000 years) in age based on records of historical inundation and (or) identification of youthful meander scars and braided bars on aerial photographs or lidar images

Qot **Stream terrace deposits (Holocene)**—Stream terrace sediments deposited in point bar and overbank environments

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

Qe **Estuarine deposits (Holocene)**—Heterogeneous mixture of coarse and fine estuarine sediment; deposited in Drakes Estero (southern edge of map) and at Toms Point on the east shore of Tomales Bay

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

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

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

Qof **Alluvial fan deposits, undivided (Holocene and late Pleistocene)**—Mapped in small valleys where separate fan, basin, and terrace units could not be delineated at map scale, and where deposits might be of either late Pleistocene or Holocene age

Qc **Colluvium (Holocene and late Pleistocene)**—Unsorted clay, silt, sand, gravel, and rock debris, in varying proportions

Qls **Landslide deposits (Holocene and Pleistocene)**—Weathered and disintegrated rocks and soil, physically weathered, mapped units range from deep-seated landslides to active colluvium

Qods **Older dune sand (late Pleistocene(?))—**Dunes stabilized by vegetation; forms large complex east of the mouth of Tomales Bay

Qml **Millerton Formation (late Pleistocene)—**Alluvial and estuarine clay, silt, sand and gravel deposited on terraces along the eastern margin of Tomales Bay

Qmt **Marine terrace deposits (late Pleistocene)—**Marine sediments uplifted to form terraces along the east coast of Tomales Bay and on the southeast coast of Bodega Bay

Qobs **Beach sand in uplifted marine terraces (late Pleistocene(?))—**Reddish-brown, friable sand and fine gravel; occur along the west coast of Tomales Point, north of Abbots Lagoon

Tp **Purisima Formation (late Pliocene to late Miocene)—**Marine siltstone, sandstone, and mudstone; locally contains diatomite

Twg **Wilson Grove Formation (Pliocene and late Miocene)—**Marine sandstone and conglomerate, occurs in northeast corner of map area, east of Tomales Bay and Bodega Bay

Tsm **Santa Margarita Sandstone (late Miocene)—**Massive marine glauconitic and bituminous arkosic sandstone

Tm **Monterey Formation (late and middle Miocene)—**Marine, thin-bedded chert, porcelanite, shale, and sandstone

Tl **Laird Sandstone (middle Miocene)—**Marine arkosic sandstone that contains basal granitic-boulder conglomerate

Kgr **Granodiorite and granite of Inverness Ridge (Late Cretaceous)—**Grandiorite and granite; aplite and alaskite dikes and masses are locally abundant

Kgd **Tonalite of Tomales Point (Late Cretaceous)—**Hornblende-biotite tonalite that contains dark diorite inclusions

**Franciscan complex**

KJfss **Sandstone and shale in Nicasio Reservoir terrane (Cretaceous and Jurassic)**

KJfgs **Greenstone in Central belt (Cretaceous and Jurassic)**

fsr **Mélange in Central belt (Cretaceous and Jurassic)—**Sheared argillite, graywacke, and minor green tuff matrix enclosing blocks and lenses of sandstone, shale, chert, metachert, and serpentinite

ss **Sandstone and shale blocks within mélange**

ch **Chert and metachert blocks within mélange**

sp **Serpentinized ultramafic rocks within mélange**

PzMz **Metamorphic rocks (Age uncertain, probably Mesozoic or Paleozoic)—**Intruded by Cretaceous granitic rocks; includes mica schist, quartzite, calc-hornfels, and marble (Clark and Brabb, 1997); occurs on east shore of Tomales Point

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