# California State Waters Map Series—Offshore of Bolinas, California

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

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

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

## Preface

In 2007, the California Ocean Protection Council initiated the California Seafloor Mapping Program (CSMP), designed to create a comprehensive seafloor map of high-resolution bathymetry, marine benthic habitats, and geology within California's State Waters. The program supports a large number of coastal-zone- and ocean-management issues, including the California Marine Life Protection Act (MLPA) (California Department of Fish and 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.

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

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[3] California Geological Survey
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raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed June 10, 2013).

The California Seafloor Mapping Program (CSMP) is a collaborative venture between numerous different federal and state agencies, academia, and the private sector. CSMP partners include the California Coastal Conservancy, the California Ocean Protection Council, the California Department of Fish and 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.

# Chapter 1. Introduction

By Guy R. Cochrane

## Regional Setting

The map area offshore of Bolinas, California, which is referred to herein as the "Offshore of Bolinas" map area (figs. 1–1, 1–2), is located in northern California, on the Pacific Coast of Marin County about 10 kilometers north of the Golden Gate. The town of Bolinas, named after a local indigenous tribe, is the largest population center along this section of coast, with a population of approximately 1,600 people. Bolinas is situated at the end of a southeast-trending terrain on the west side of the San Andreas Fault that also protects a natural harbor. The harbor lies in Bolinas Lagoon, which is separated from Bolinas Bay by a spit. The harbor is host to two marinas, a boat launch, and two fishing ports. Little recreational boat activity takes place in the harbor. The coastal lands within the Offshore of Bolinas map area lie entirely within the Point Reyes National Seashore, which limits development and allows existing ranching and farming to continue.

The Offshore of Bolinas map area lies offshore of the northwest-trending Coast Ranges (fig. 1–1), which are roughly parallel to the San Andreas Fault Zone (California Geological Survey, 2002). The western margin of North America is the only continental margin in the world delineated largely by transform faults such as the San Andreas Fault (Dickinson, 2004). The Coast Ranges lie east of the San Andreas Fault. The coastal geomorphology is controlled by late Pleistocene to Holocene slip along the fault (Dickinson and others, 2005). Bolinas Bay and Lagoon have formed where a regional depression along the fault zone intersects the coast. A northward bend in the San Andreas Fault to the north, combined with right-lateral movement, has caused regional extension and the formation of a sediment basin on the continental shelf in, and southeast of, Bolinas Bay (Ryan and others, 2008).

With the exception of the area adjacent to Bolinas Bay, the coast in the map area consists of high coastal bluffs and vertical sea cliffs (Griggs and others, 2005). The uplifted headland upon which the town of Bolinas is situated is part of a larger uplifted area that includes exposed bedrock offshore. Uplift in this map area has resulted in relatively shallow depths within California's State Waters (0 to 40 m) and, thus, little accommodation space for sediment accumulation. Sediment is found in the extensional basin southeast of Bolinas, as well as on the shelf offshore of uplifted coastal areas, where, within California's State Waters, depths can exceed 40 m. Wave energy keeps the uplifted bedrock areas clear of sediment, and rippled sediment in the outer shelf indicates some mobility.

Coastal sediment transport in the Offshore of Bolinas map area is characterized by north-to-south littoral transport of sediment that is derived mainly from ephemeral streams and local coastal erosion (Hapke and others, 2006). Beyond California's State Waters, canyons that incise the slope have been disconnected from coastal streams by rising sea level, which has risen about 125 m since the lowstand associated with the Last Glacial Maximum about 18,000 to 20,000 years ago (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Lambeck and others, 2002). In the map area, no major submarine canyons extend up past the shelf break and into the nearshore to receive littoral drift. Griggs and others (2005) categorized erosion of the coastline in the map area as high risk, as it is characterized by steep cliffs and large-scale landsliding. The sand spit that separates Bolinas Lagoon from Bolinas Bay is highly developed, and its homes are at risk during storms, especially those from the south.

The benthic species observed in the Offshore of Bolinas map area are natives of the cold-temperate biogeographic zone named either the "Oregonian province" (Briggs, 1974) or the "northern California ecoregion" (Spalding and others, 2007). This biogeographic province is maintained by the long-term stability of the southward-flowing California Current, an eastern limb of the North Pacific subtropical gyre that flows from Oregon to Baja California. At its midpoint off central California, the

California Current transports subarctic surface (0–500 m deep) waters southward, about 150 to 1,300 km from shore (Lynn and Simpson, 1987; Collins and others, 2000). Seasonal northwesterly winds (Inman and Jenkins, 1999) that are, in part, responsible for the California Current, generate coastal upwelling. The south end of the Oregonian province is at Point Conception (about 425 km south of the map area), although its associated phylogeographic group of marine fauna may extend beyond to the area offshore of Los Angeles in southern California (Dawson and others, 2006). The ocean off central California has seen a warming over the last 50 years that is driving an ecosystem shift from the productive subarctic regime towards a depopulated subtropical environment (McGowan and others, 1998).

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

## Publication Summary

This publication about the Offshore of Bolinas map area includes ten map sheets that contain explanatory text, in addition to this descriptive pamphlet and a data catalog of geographic information system (GIS) files. Sheets 1, 2, and 3 combine data from four different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data reveal a range of physiographic features (highlighted in the perspective views on sheet 4) such as the flat, sediment-covered inner continental to midcontinental shelf, as well as shallow "scour depressions" and local, tectonically controlled bedrock uplifts. To validate geological and biological interpretations of the sonar data shown in sheets 1, 2, and 3, the U.S. Geological Survey towed a camera sled over specific offshore locations, collecting both video and photographic imagery; this "ground-truth" surveying data is summarized on sheet 6. Sheet 5 is a "seafloor character" map, which classifies the seafloor on the basis of depth, slope, rugosity (ruggedness), and backscatter intensity and which is further informed by the ground-truth-survey imagery. Sheet 7 is a map of "potential habitats," which are delineated on the basis of substrate type, geomorphology, seafloor process, or other attributes that may provide a habitat for a specific species or assemblage of organisms. Sheet 8 compiles representative seismic-reflection profiles from the map area, providing information on the subsurface stratigraphy and structure of the map area. Sheet 9 shows the distribution and thickness of young sediment (deposited over the last about 21,000 years, during the most recent sea-level rise) in both the map area and the larger Bolinas to Pescadero region, interpreted on the basis of the seismic-reflection data. Sheet 10 is a geologic map that merges onshore geologic mapping (compiled from existing maps by the California Geological Survey) and new offshore geologic mapping that is based on integration of high-resolution bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8).

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

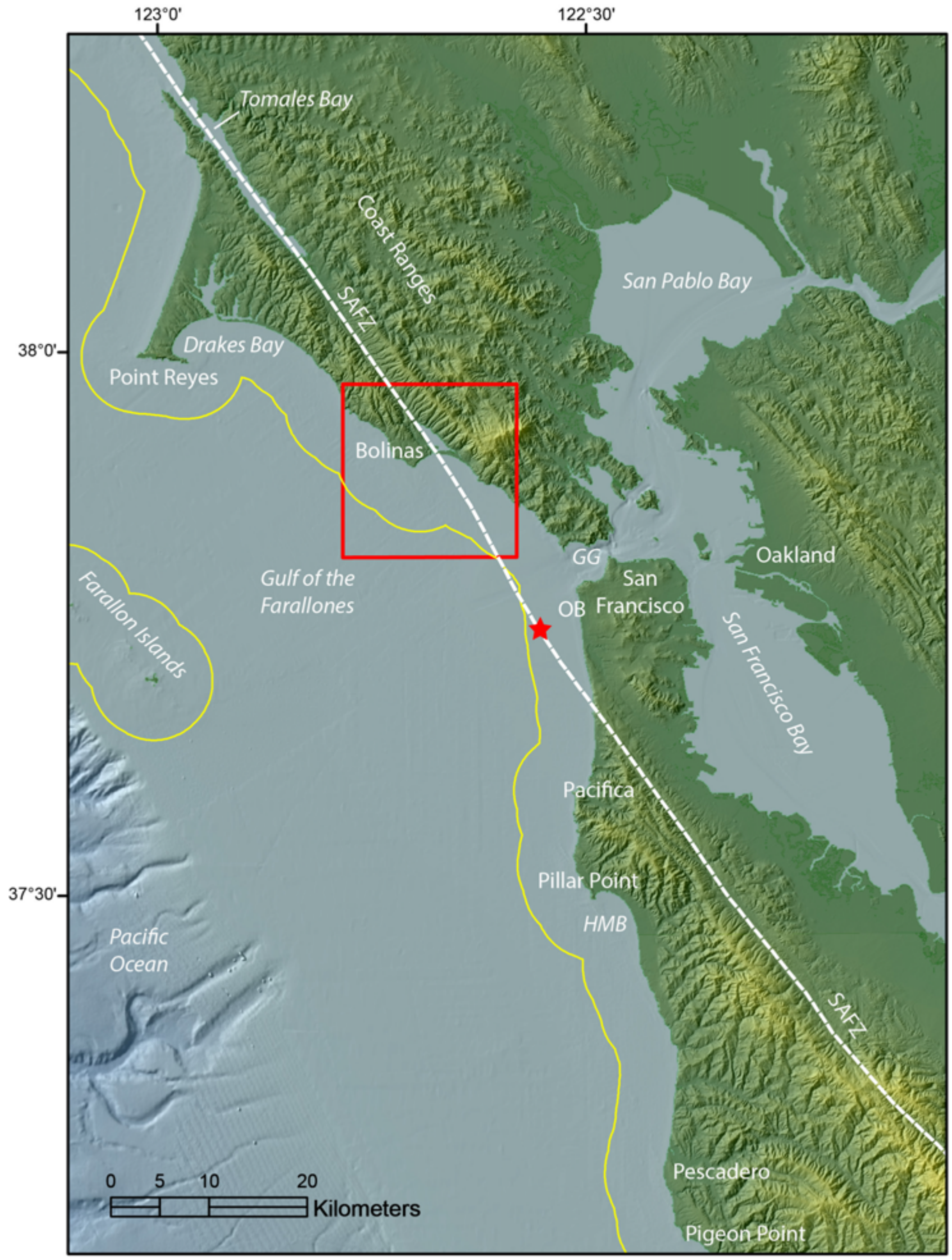


**Figure 1–1.** Physiography of Bolinas to Pescadero region and its environs. Box shows Offshore of Bolinas map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Red star shows epicenter of great 1906 California earthquake. Other abbreviations: GG, Golden Gate; HMB, Half Moon Bay; OB, Ocean Beach.

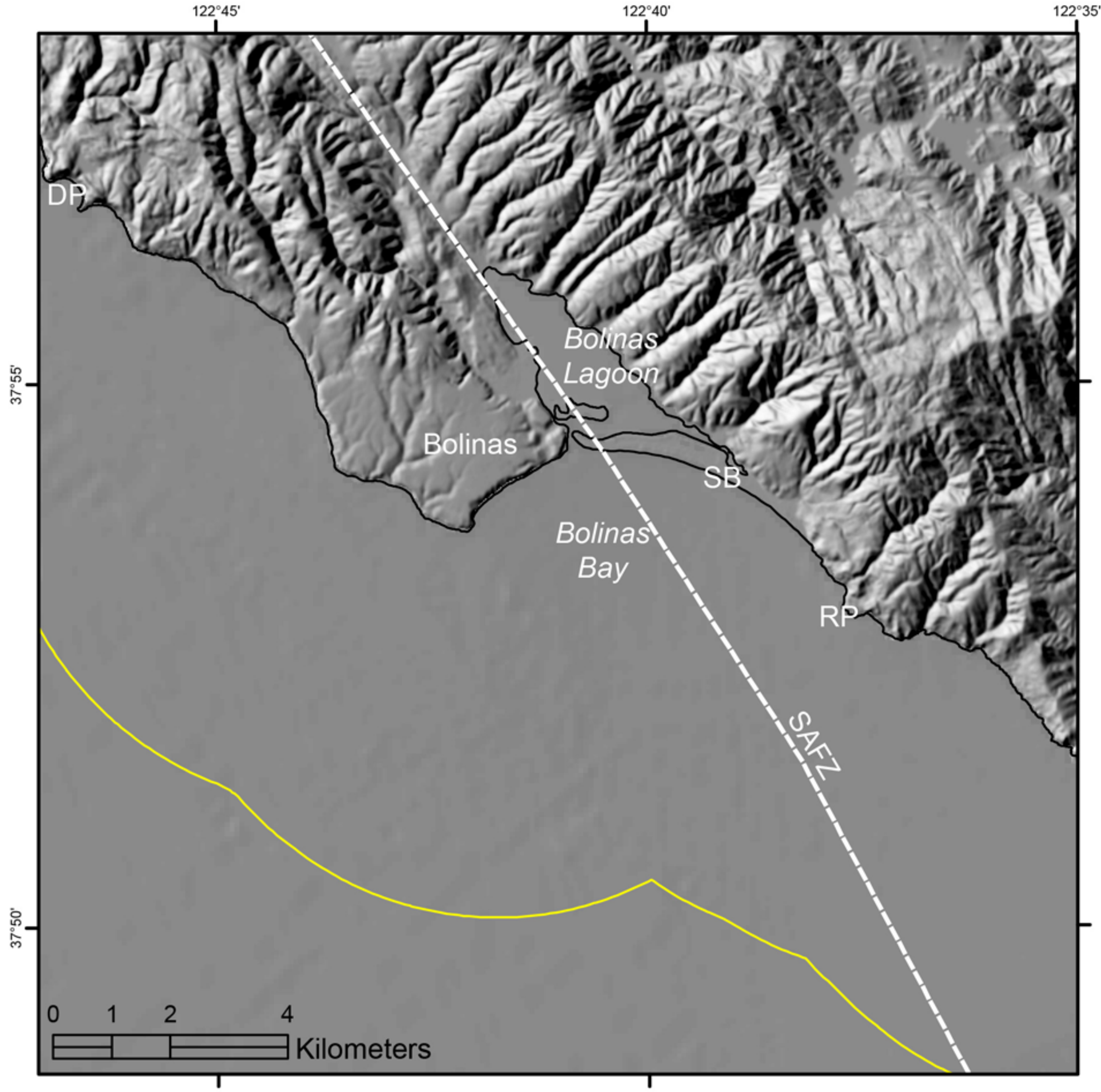


**Figure 1–2.** Coastal geography of Offshore of Bolinas map area. Yellow line shows limit of California's State Waters. Dashed white line shows trace of San Andreas Fault Zone (SAFZ). Other abbreviations: DP, Double Point; RP, Rocky Point; SB, Stinson Beach.

# Chapter 2. Bathymetry and Backscatter-Intensity Maps of the Offshore of Bolinas 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 Bolinas map area in northern California were generated from bathymetry and backscatter data collected by California State University, Monterey Bay (CSUMB), by Fugro Pelagos, and by Moss Landing Marine Laboratories (fig. 1 on sheets 1, 2, 3). 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 468-kHz SWATHplus and 250-kHz GeoSwath interferometric systems. The nearshore area from south of Bolinas Lagoon to Stinson Beach was mapped by Fugro Pelagos in 2009 for the National Oceanic and Atmospheric Administration (NOAA), and only bathymetry data were collected. These mapping missions combined to collect both bathymetry (sheets 1, 2) and acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 3-nautical-mile limit of California's State Waters.

During the mapping missions, an Applanix POS MV (Position and Orientation System for Marine Vessels) was used to accurately position the vessels during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm); in addition, sound-velocity profiles were collected with an Applied Microsystems (AM) SVPlus sound velocimeter. 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). 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.

Reson 7125 and 8101 backscatter data were postprocessed using the CARIS 7.0 integration of Geocoder software. Within Geocoder, the backscatter intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. After the lines were corrected, they were mosaicked into a 1-m-resolution image. Overlap between parallel lines was resolved using a priority table whose values were based on the distance of each sample from the ship track, with the samples that were closest to and furthest from the ship track being given the lowest priority. An anti-aliasing algorithm was also applied. The mosaics were then exported as georeferenced TIFF images, imported into a geographic information system (GIS), and converted to GRIDs at 2-m resolution. SWATHplus backscatter data were postprocessed using U.S. Geological Survey 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. GeoSwath backscatter data were postprocessed with GeoSwath 32 software to remove signal artifacts and then converted to GRIDs using Gridder 32 software (Erdey-Heydorn, 2008).

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 Bolinas 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).

Bathymetric contours (sheets 1, 2, 3, 5, 7, and 10) were generated at 10-m intervals from the merged 2-m-resolution bathymetric surface. The merged surface was smoothed using the Focal Mean tool in ArcGIS and a circular neighborhood that has a radius of between 20 and 30 m (depending on the location). The contours were generated from this smoothed surface using the Spatial Analyst Contour tool in ArcGIS. The most continuous contour segments were preserved; smaller segments and isolated island polygons were excluded from the final output. The contours were then clipped to the boundary of the map area.

The acoustic-backscatter imagery from each different mapping system and processing method were merged into their own individual grids. These individual grids, which cover different areas, were combined in a GIS to create the composite 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 1-m-resolution topographic-lidar data collected by Earth Eye in 2010 for San Francisco State University and the U.S. Geological Survey (available at http://ned.usgs.gov/).

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

By Peter Dartnell

Mapping California's State Waters has produced a vast amount of acoustic and visual data, including bathymetry, acoustic backscatter, seismic-reflection profiles, and seafloor video and photography. These data are used by researchers to develop maps, reports, and other tools to assist in the coastal and marine spatial-planning capability of coastal-zone managers and other stakeholders. For example, seafloor-character (sheet 5), habitat (sheet 7), and geologic (sheet 10) maps of the Offshore of Bolinas 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 Bolinas 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 blueish greens represent deeper depths. Topographic data were shown in gray shades. Digital orthophotographs were draped over the topography data, and the acoustic-backscatter geoTIFF images were draped over the bathymetry data. The colored bathymetry, topography, and draped backscatter were then tilted and panned to create the perspective views such as those shown in figures 1 through 6 on sheet 4. These views highlight the diverse seafloor environments in the Offshore of Bolinas map area, which include large areas of featureless, sediment-covered seafloor and extensive areas of folded and faulted bedrock.

Block diagrams that combine the bathymetry with seismic-reflection-profile data help integrate surface and subsurface observations, especially stratigraphic and structural relations (for example, fig. 6 on sheet 4). These block diagrams were created by converting digital seismic-reflection-profile data (see sheet 8) into TIFF images, while taking note of the starting and ending coordinates and maximum and minimum depths. The images were then imported into the Fledermaus® software as vertical images and merged with the bathymetry imagery.

# Chapter 4. Seafloor-Character Map of the Offshore of Bolinas 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 Bolinas 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 Bolinas map area (sheet 5) was produced using video-supervised maximum-likelihood classification of the bathymetry and intensity of return from sonar systems, following the method described by Cochrane (2008). The two variants used in this classification were backscatter intensity and derivative rugosity. The rugosity calculation was performed using the Terrain Ruggedness (VRM) tool within the Benthic Terrain Modeler toolset v. 3.0 (Wright and others, 2012; available at http://esriurl.com/5754).

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

On the seafloor-character map (sheet 5), the four substrate classes have been colored to indicate the California MLPA depth zones and the Coastal and Marine Ecological Classification Standard (CMECS) slope zones (Madden and others, 2008) in which they belong. The California MLPA depth zones are Depth Zone 1 (intertidal), Depth Zone 2 (intertidal to 30 m), Depth Zone 3 (30 to 100 m), Depth Zone 4 (100 to 200 m), and Depth Zone 5 (greater than 200 m); in the Offshore of Bolinas map area, only Depth Zones 2 and 3 are present. The slope classes that represent the CMECS slope zones are

Slope Class 1 = flat (0° to 5°), Slope Class 2 = sloping (5° to 30°), Slope Class 3 = steeply sloping (30° to 60°), Slope Class 4 = vertical (60° to 90°), and Slope Class 5 = overhang (greater than 90°); in the Offshore of Bolinas 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 is also summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 66.1 percent (72.7 $km^2$) of the map area: 51.0 percent (56.1 $km^2$) is in Depth Zone 2, and 15.1 percent (16.6 $km^2$) 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 22.2 percent (24.5 $km^2$) of the map area: 18.8 percent (20.8 $km^2$) is in Depth Zone 2, and 3.4 percent (3.7 $km^2$) is in Depth Zone 3. Rock and boulder, rugose (rock outcrops and boulder fields having high surficial complexity) makes up 7.9 percent (8.7 $km^2$) of the map area: 7.5 percent (8.3 $km^2$) is in Depth Zone 2, and 0.4 percent (0.4 $km^2$) 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 3.8 percent (4.2 $km^2$) of the map area: 3.8 percent (4.2 $km^2$) is in Depth Zone 2, and less than 0.1 percent (<0.1 $km^2$) is in Depth Zone 3.

A small number of video observations were used to supervise the numerical classification of the seafloor. All video observations (see sheet 6) are used for accuracy assessment of the seafloor-character map after classification. In addition, owing to the limited visibility throughout the video survey in this region, sediment samples also were used to ground-truth survey the classification. These samples were collected by the USGS in 2010 using a Smith McIntyre grab sampler and photographed in the field. 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 Bolinas map area is covered predominantly by Class I sediments mostly composed of sand. Numerous exposures of rugose bedrock (Class III) are present in the north half of the map area, offshore of the Bolinas headland. The rock outcrops are covered with varying thicknesses of fine (Class I) to coarse (Class II) sediment. Several smaller areas of scour depressions (Class IV) also have been identified adjacent to rock outcrops.

The classification accuracy of Classes I and IV (83 percent and 98 percent accurate, respectively; table 4–2) is determined by comparing shipboard video observations, sediment samples, and the classified map. Only three samples were retrieved from Class III rock outcrops and boulders. Two of the three samples were within the 10-m buffer zone of Class III pixels on the map, and the third was 13 m away. The limited number of samples and the intermittent sediment cover on the rock areas (Class III pixels mixed with Class II and Class IV) caused the low accuracy (27 percent) in these regions. The weaker (37 percent) agreement in Class II (mixed smooth sediment and rock and flat rock outcrop) likely is due to the relatively narrow and intermittent nature of transition zones from sediment to rock and also the size of the buffer; a strong likelihood exists for a Class II (mixed) pixel to be interspersed with pixels belonging to other classes. A single buffered observation locale of 78 pixels, therefore, is likely to be interspersed with other classes of pixels in addition to Class II. Percentages for presence/absence within a buffer also were calculated as a better measure of the accuracy of the classification for patchy rock habitat. The presence/absence accuracy was found to be significant for all classes (95 percent for Class I, 79 percent for Class II, 67 percent for Class III, and 100 percent for Class IV).

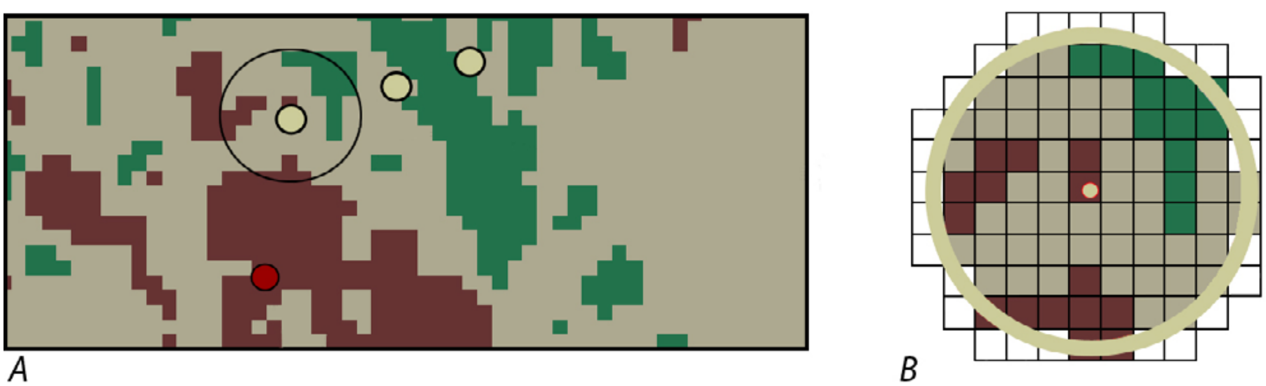


**Figure 4–1.** Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

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

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

| Primary-substrate component | Secondary-substrate component | Abiotic seafloor complexity | Low-visibility observations |
|---|---|---|---|
| Class I | | | |
| sand | sand | low | |
| Class II | | | |
| sand | boulders | moderate | |
| sand | rock | moderate | |
| Class III | | | |
| rock | rock | moderate | |
| Class IV | | | |
| sand | sand | low | |
| | | | megaripples |
| | | | oscillatory megaripples |
| | | | depression |

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

[Accuracy assessments are based on video observations and sediment samples]

| Class | Number of observations | % majority | % presence/absence |
|---|---|---|---|
| I—Fine- to medium-grained smooth sediment | 144 | 82.6 | 95.1 |
| II—Mixed smooth sediment and rock | 14 | 37.5 | 78.6 |
| III—Rock and boulder, rugose | 3 | 27.2 | 66.7 |
| IV—Medium- to coarse-grained sediment (in scour depressions) | 9 | 98.1 | 100.0 |

# Chapter 5. Ground-Truth Studies for the Offshore of Bolinas 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 Bolinas 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 over the seafloor at speeds of between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 3 trackline kilometers of video and 28 still photographs, in addition to 88 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

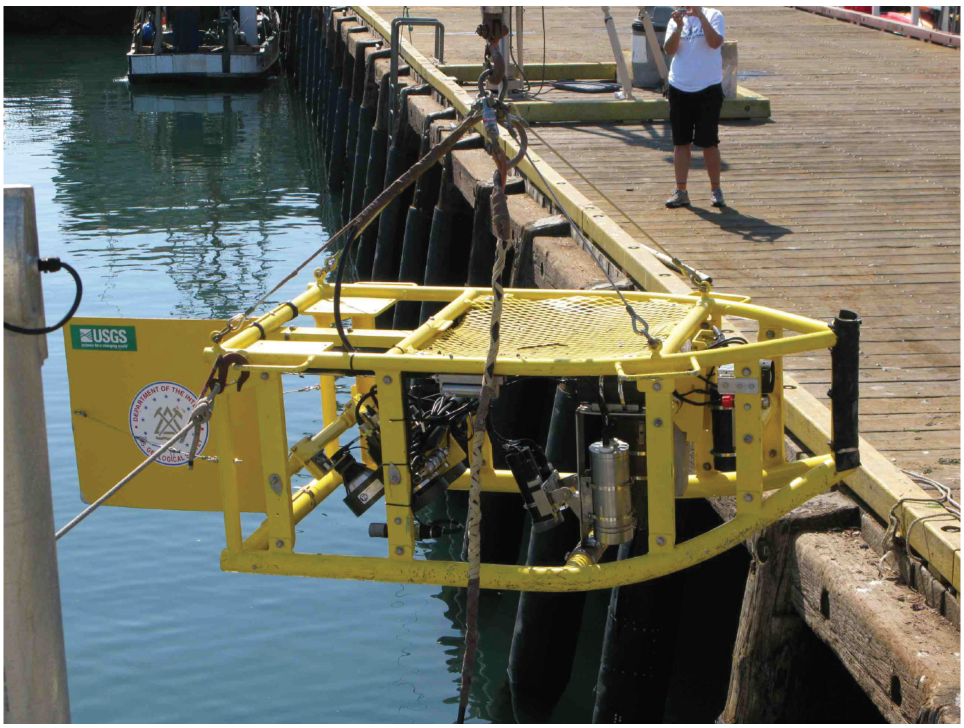


**Figure 5–1.** Photograph of camera sled used in USGS 2008 ground-truth survey.

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

The camera-sled tracklines (shown by colored dots on the map on sheet 6) are sited in order to visually inspect areas representative of the full range of bottom hardness and rugosity in the map area. The video is fed in real time to the research vessel, where USGS and National Oceanic and Atmospheric Administration (NOAA) scientists record both the geologic and biologic character of the seafloor. While the camera is deployed, several different observations are recorded for a 10-second period once every minute, using the protocol of Anderson and others (2007). Observations of primary substrate, secondary 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, B; the location of Box C is not shown because it covers the entire Offshore of Bolinas map area); for each view, the box shows the locations (indicated by colored stars) of representative seafloor photographs and (or) sediment-sample 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 Bolinas map area, the majority of useful seafloor observations were obtained in areas that contain sand-dominated sedimentary deposits. Areas of rocky habitat in the northwestern part of the map area were undersampled. Robust models of the distribution of flora and fauna in the map area will require additional video-surveying effort.

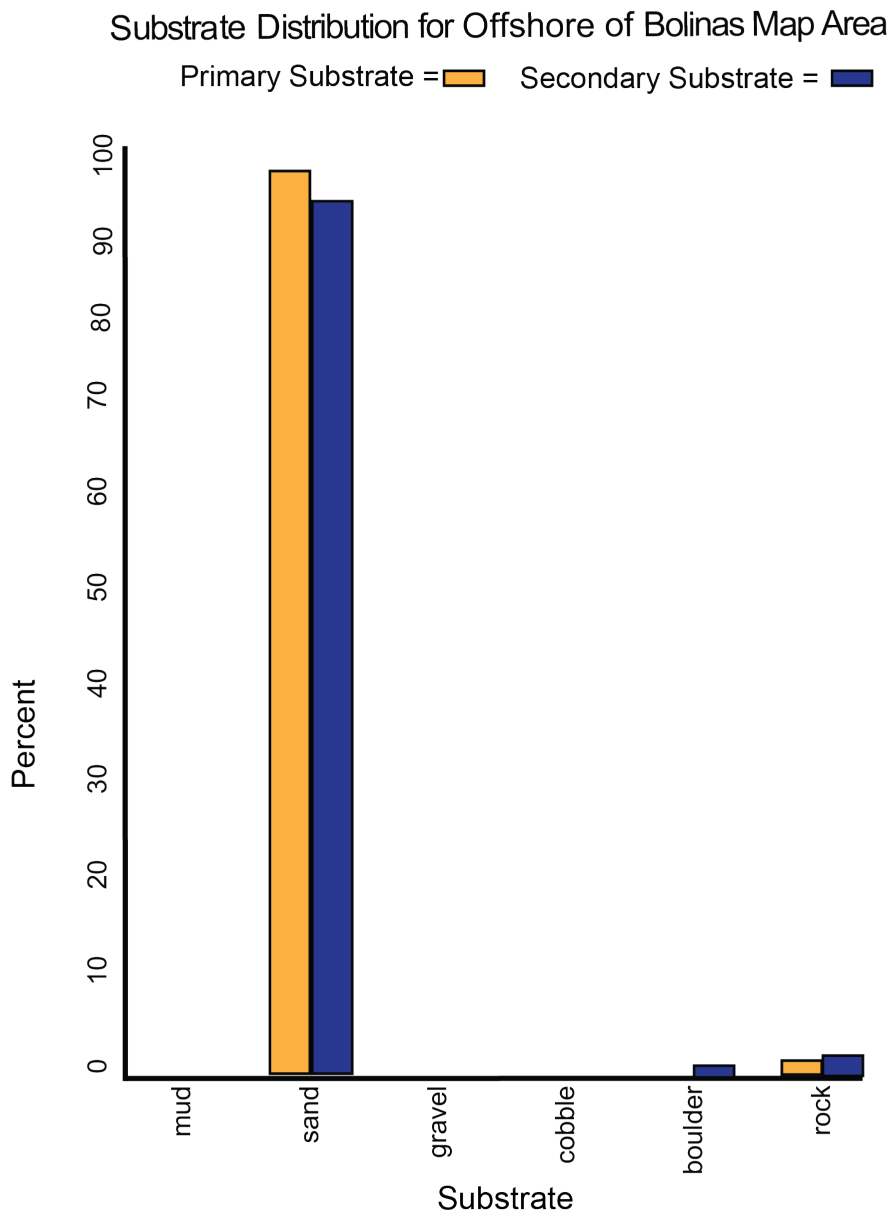


**Figure 5–2.** Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Bolinas map area.

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

By H. Gary Greene and Charles A. Endris

The map on sheet 7 shows “potential” marine benthic habitats in the Offshore of Bolinas 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 Bolinas 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 Bolinas 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 Bolinas map are explained in detail below (note, however, that not all categories may be used in a particular map area, given the study objectives, data availability, or data quality); attribute codes in each category are depicted on the map by the letters and, in some cases, numbers that make up the map-unit symbols:

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

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

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

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

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

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

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

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

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

## Examples of Attribute Coding

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

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

## Map Area Habitats

Delineated in the Offshore of Bolinas map area are 13 potential marine benthic habitat types, all of which are located on the continental shelf ("Shelf" megahabitat). These include rippled, unconsolidated sediment; dynamic features such as sediment waves; "mixed" hard-soft habitats; deformed and differentially eroded sedimentary-bedrock outcrops; and boulders and pinnacles. Backscatter data show that most of the map area is underlain by soft sediment, consistent with the interpretation that unconsolidated sediments are the primary habitat in the map area, with well-exposed deformed and differentially eroded sedimentary bedrock being the next most prominent habitat type.

Sediment transport is primarily to the southeast, and sedimentary processes, which are quite active in the map area, produce mobile sand sheets. In addition, erosion through shelf sediments down to a coarser lag has produced sediment-filled scour depressions that resemble "ripple scour depressions" of Cacchione and others (1984) and Phillips and others (2007), found mainly on the shelf in the northwestern part of the map area.

Of the 119.24 $km^2$ in the map area, 75.3 $km^2$ (63.2 percent) is classified as soft, unconsolidated sediment, 14.69 $km^2$ (12.3 percent) is classified as mixed substrate (soft sediment over hard substrate), and 29.26 $km^2$ (24.5 percent) is classified as hard substrate.

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

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

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

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

## Data Acquisition

Data for the seismic-reflection profiles shown in figures 1, 2, and 3 on sheet 8 were collected in 2009 on U.S. Geological Survey (USGS) cruise S–8–09–NC. Data for the seismic-reflection profiles shown in figures 6, 7, 8, and 9 on sheet 8, and figure 1 on sheet 9, were collected in 2006 on USGS cruise L–1–06–NC. Both cruises collected data using the SIG 2Mille minisparker system. The system 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).

Data for the profiles shown in figures 5, 10, and 11 on sheet 8 were collected in 1995 on USGS cruise G–2–95–SF (Childs and others, 2000; Bruns and others, 2002). Two 0.65-L air guns fired at 12.5-m intervals provided the seismic source, and data were digitally recorded on a 24-channel, 150-m-long streamer merged with GPS navigation data. Data-processing steps included deconvolution, automatic gain control, filtering at 50 to 160 Hz, stacking, and migration.

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

## Geologic Structure and Recent Deformation

The Offshore of Bolinas map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active faults that cumulatively form a distributed shear zone; these active faults include the San Andreas Fault, the east strand of the San Gregorio Fault Zone, the Golden Gate Fault, and the Potato Patch Fault (see sheets 9, 10; see also, Jachens and Zoback, 1999; Zoback and others, 1999; Bruns and others, 2002; Parsons and others, 2005; Ryan and others, 2008). The offshore parts of these faults are identified on seismic-reflection profiles on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as reflection presence, amplitude, frequency, geometry, continuity, and vertical sequence. The San Andreas Fault, which is the dominant plate-boundary structure, extends northwest through the southern part of the map area before moving onshore at Bolinas Lagoon. In this area, the San Andreas Fault has an estimated slip rate of 17 to 24 mm/yr (U.S. Geological Survey and California Geological Survey, 2010).

The San Gregorio Fault Zone, another major strike-slip fault system within the distributed transform plate boundary, extends predominantly in the offshore for about 400 km along the California coast. Cumulative lateral slip is estimated to be about 4 to 10 mm/yr (U.S. Geological Survey and California Geological Survey, 2010) near San Francisco. Slip on the San Gregorio Fault Zone is divided between an east strand (figs. 6, 7, 8, 10 on sheet 8), which converges with the San Andreas Fault in the map area and also moves onshore at Bolinas Lagoon (see sheets 9, 10), and a west strand, which lies southwest of the map area and may merge with the northwest-striking, northeast-dipping Point Reyes Fault Zone (Bruns and others, 2002; Ryan and others, 2008), which lies a few kilometers southwest of the map area outside California's State Waters. Grove and others (2010) determined uplift rates of about 1 mm/yr for emergent marine terraces along the Bolinas headland just west of Bolinas, which they linked to a position on the upthrown north flank of the Point Reyes Fault Zone. The Potato Patch Fault (figs. 5, 7, 9 on sheet 8), which lies between the San Andreas Fault and the east strand of the San Gregorio Fault Zone between Pacifica and Bolinas, also converges northward with the San Andreas Fault (sheet 9) south of Bolinas Lagoon. The Golden Gate Fault (figs. 5, 7, 9 on sheet 8; see also, sheet 9) lies east of, and is parallel to, the San Andreas Fault between San Francisco and Bolinas.

Zoback and others (1999) and Ryan and others (2008) noted a northward bend in the strike (from about 325° to 330°) of both the San Andreas and San Gregorio Faults offshore of San Francisco, resulting in a local change from contractional to extensional crustal deformation. The inferred extensional setting is consistent with subsidence of the San Francisco ebb-tidal delta and development of the prominent San Andreas graben (see figs. 7, 9 on sheet 8; Maps A, B, D on sheet 9; see also, Cooper, 1973; Bruns and others, 2002; Ryan and others, 2008). This basin, which is about 7 km long and 2.5 km wide, is bounded on the southwest by the east strand of the San Gregorio Fault Zone (and the Bolinas shelf) and on the northeast by the Golden Gate Fault (and the Marin shelf). The basin floor dips gently westward toward the San Andreas Fault, along which the basin is deepest and the basin fill is thickest. The abrupt northern margin of the basin (see Maps A, B, D on sheet 9) could have formed either as (1) an extensional, en echelon normal fault that resulted from eastward transfer of slip from the San Andreas Fault to the Golden Gate Fault, or (2) a gentle, northwest-striking restraining bend in the Golden Gate Fault as it converges with the San Andreas Fault to the north. The southern margin of the basin, whose slope appears to be more gradual, lies offshore of San Francisco within a sea-level-lowstand paleovalley.

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) 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 number of earthquakes in the region clearly occur within the broad San Andreas Fault Zone between Pacifica and Bolinas; events west of the east strand of the San Gregorio Fault and east of the Golden Gate Fault are much less common. Map E also shows the inferred location of the devastating great 1906 California earthquake (M7.8, 4/18/1906), thought to have nucleated on the San Andreas Fault offshore of San Francisco (see, for example, Bolt, 1968; Lomax, 2005).

## Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Bolinas map area, which includes parts of three tectonically controlled sediment-thickness domains: the Bolinas shelf, the San Andreas graben, and the Marin shelf (see Maps A, B, D on sheet 9). The seafloor is relatively flat (less than 0.3°) and shallow (less than 30 m) in the entire map area; however, the seafloor of the San Andreas graben and the Marin shelf east of the San Gregorio Fault is smooth and covered with sediment, whereas the seafloor west of the San Gregorio Fault has extensive areas of bedrock outcrop from the nearshore to depths of about 25 m (see sheets 1, 2).

These three sediment-thickness domains are variably underlain by uppermost Pleistocene and Holocene sediment deposited in the last about 21,000 years during the sea-level rise that followed the Last Glacial Maximum (LGM) and the last major lowstand. Sea level was about 125 m lower during the LGM, at which time the shoreline was more than 45 km west of San Francisco near the Farallon Islands. The post-LGM sea-level rise was rapid (about 9 to 11 m per thousand years) until about 7,000 years ago, when it slowed considerably to about 1 m per thousand years (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006; Stanford and others, 2011).

The sediments deposited during this latest Pleistocene and Holocene sea-level rise are shaded blue in the seismic-reflection profiles on sheet 8 (figs. 2, 3, 6, 7, 8, 9). This post-LGM stratigraphic unit is typically characterized either by “acoustic transparency” or by parallel, low-amplitude, low- to high-frequency, continuous to moderately continuous, diffuse reflections (terminology from Mitchum and others, 1977). The acoustic transparency (that is, lack of internal reflections) can be caused by extensive wave winnowing, resulting in a uniform sediment grain size, hence, the lack of acoustic-impedance contrasts needed to produce seismic reflections. The contact between these sediments and the underlying strata is a transgressive erosional surface (see, for example, Catuneanu, 2006), which commonly is marked by angularity, channeling, or a distinct upward change to lower amplitude, more diffuse reflections. It is emphasized that the base of this unit is an interpretation somewhat hindered by both acoustic transparency and by “acoustic masking,” which is associated with the presence of interstitial gas within the sediment (Fader, 1997; Ryan and others, 2008).

## 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 Bolinas map area (Maps A, B) and, to establish regional context, for a larger area (about 91 km of coast) that extends from the Bolinas area to Pescadero Point (Maps C, D). To make these maps, water bottom and depth to base of the post-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 57 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 San Andreas, San Gregorio, and Golden Gate Faults disrupt the sediment sequence in the region. The thickness data points also are dense along tracklines (about 1 m apart) and sparse between tracklines (1 km apart), resulting in contouring artifacts. To incorporate the effect of the faults, to remove irregularities from interpolation, and to reflect other geologic information and complexity, the resulting interpolated contours were modified. Contour modifications and regridding were repeated several times to produce the final regional sediment-thickness map (Maps B, D). Information for the depth to base of the post-LGM unit (Maps A, C) was generated by adding the thickness data to water depths determined by multibeam bathymetry (see sheet 1).

The thickness of the post-LGM unit in the Offshore of Bolinas map area ranges from 0 to 57 m (Map B on sheet 9), and the depth to the base of this unit ranges from less than 10 to 78 m (Map A on sheet 9). A significant difference in thickness exists between the Bolinas shelf, which has a mean sediment thickness of 0.8 m, and the San Andreas graben, which has a mean sediment thickness of 34.7 m (table 7–1). The east strand of the San Gregorio Fault Zone forms the boundary between these two distinct sediment-thickness domains, but the largest amount of vertical fault offset is found within the San Andreas graben, east of, and along, the San Andreas Fault (see for example, figs. 7, 9 on sheet 8). Sediment beneath the Marin shelf, north and east of the San Andreas graben, has an intermediate mean sediment thickness of 6.1 m. The San Andreas graben occupies about 18 percent of the map area, but it contains about 77 percent of the volume of the map area's post-LGM sediments (table 7–1). In contrast, the Bolinas shelf occupies about 60 percent of the map area but contains just 6 percent of its total sediment.

The thin (0 to 5 m) sediment cover on the Bolinas shelf west of the San Gregorio Fault results from a lack of sediment "accommodation space" (Catuneanu, 2006) that is here associated with high rates of tectonic uplift (Grove and others, 2010) and strong wave action. The uplift exposes much of the shallow shelf to the high wave energy that is characteristic of this region (Barnard and others, 2007), so that sediments are efficiently reworked and transported off the inner shelf to deeper water. In contrast, rapid subsidence in the San Andreas graben to the east of the east strand of the San Gregorio Fault Zone has provided significant accommodation space for accumulation of a very thick section of post-LGM sediment.

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

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

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

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

| **Regional sediment-thickness domains in Bolinas to Pescadero region** | | | |
|---|---|---|---|
| | **Area (km$^2$)** | **Mean sediment thickness (m)** | **Sediment volume ($10^6$ m$^3$)** |
| Entire Bolinas to Pescadero region | 529 | 6.2 | 3,286 |
| (1) Bolinas shelf, west of east strand of San Gregorio Fault Zone | 72 | 0.8 | 59 |
| (2) San Andreas graben, between San Gregorio Fault Zone and Golden Gate Fault | 27 | 33.5 | 906 |
| (3) Marin shelf, northeast and northwest of San Andreas graben, north of San Francisco ebb-tidal delta paleovalley | 44 | 8.1 | 355 |
| (4) San Francisco ebb-tidal delta paleovalley | 35 | 19.5 | 685 |
| (5) Pacifica-Pescadero shelf | 351 | 3.6 | 1,281 |
| **Sediment thickness in Offshore of Bolinas map area** | | | |
| Offshore of Bolinas map area | 121 | 8.1 | 975 |
| Bolinas shelf, west of east strand of San Gregorio Fault Zone | 72 | 0.8 | 59 |
| San Andreas graben, between San Gregorio Fault Zone and Golden Gate Fault | 22 | 34.7 | 751 |
| Marin shelf, northeast and northwest of San Andreas graben, north of San Francisco ebb-tidal delta paleovalley | 27 | 6.1 | 165 |

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

By Samuel Y. Johnson, H. Gary Greene, Michael W. Manson, Charles A. Endris, Stephen R. Hartwell, and Janet T. Watt

## Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Bolinas 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). The relative proportions of all offshore map units are shown in table 8–1.

Onshore geology was compiled from California Geological Survey (1974), Clark and Brabb (1997), Blake and others (2000), and Witter and others (2006). Unit ages, which are derived from these sources, reflect local stratigraphic relations.

The continental shelf within California's State Waters in the Offshore of Bolinas map area is shallow (less than about 30 m) and flat, with a very gentle (less than 0.3°) offshore dip. The seafloor of the Marin shelf east of the San Andreas Fault is smooth and covered with sediment, whereas the seafloor of the Bolinas shelf west of this fault has extensive areas of bedrock outcrop from the nearshore to depths of about 25 m, as well as much less sediment cover (see sheets 1, 2, 8, 9). Shelf morphology and evolution are the result of the interplay between local tectonics (local faulting, folding, uplift, and subsidence) and sedimentation as sea level rose about 125 to 130 m during the last about 21,000 years (see, for example, Lambeck and Chappell, 2001; Stanford and others, 2011). This sea-level rise lead to both the progressive eastward migration (a few tens of kilometers) of the shoreline and wave-cut platform and the associated transgressive erosion and deposition (see, for example, Catuneanu, 2006). The Offshore of Bolinas map area is now an open-ocean shelf that is subjected to the full, and sometimes severe, wave energy and strong currents of the Pacific Ocean (Storlazzi and Wingfield, 2005).

Given the relatively shallow depths and high energy, modern shelf deposits are mostly sand (unit Qms). Coarser grained sands and gravels (units Qmsc and Qmss) are recognized primarily on the basis of bathymetry and high backscatter (sheets 1, 2, 3). Unit Qmsc is mapped in two areas, (1) west of the rocky outcrops on the Bolinas shelf, and (2) in three mounds south of Bolinas, along the San Gregorio Fault near the limit of California's State Waters, at water depths of about 25 m. The largest of these mounds is about 450 m long and 70 m wide, and it has 80 cm of positive relief.

Unit Qmss is much more extensive and forms erosional lags in scour depressions (see, for example, Cacchione and others, 1984; Hallenbeck and others, 2012; Davis and others, 2013) that typically are a few tens of centimeters deep and bounded by mobile sand sheets. The depressions are mapped in four distinct locations. (1) The first unit Qmss location lies adjacent to bedrock outcrops within 2 km of the shoreline south of Double Point (near the west edge of the map area), at water depths of 10 to 25 m. (2) The second unit Qmss location is in an area that extends from about 1 to 6 km south of Bolinas Lagoon, along the east flank of the exposed bedrock on the Bolinas shelf, at similar water depths. (3) The third, more restricted unit Qmss location is near the east edge of the map area, about 4 km southeast of Rocky Point, adjacent to and offshore of small bedrock uplifts within 1 km of the shoreline, at water depths of about 10 to 12 m. (4) The fourth unit Qmss location, 2 km south of Stinson

Beach and 2 km east of the Marin shelf seafloor bedrock outcrops, is notably different; the single Qmss polygon in this area encloses more than 100 much smaller (lengths less than 20 m) oval depressions and intervening sand sheets. This mode of occurrence could result from sediment infilling of an area formerly characterized by one or more larger scour depressions.

Such scour depressions are common along this stretch of the California coast (see, for example, Cacchione and others, 1984; Hallenbeck and others, 2012; Davis and others, 2013) where offshore sandy sediment can be relatively thin (and, thus, is unable to fill the depressions) owing to lack of sediment supply from rivers and also to significant erosion and offshore transport of sediment during large northwest winter swells. Although the general areas in which both unit Qmss scour depressions and surrounding mobile 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.

Areas where shelf sediments form thin (less than 2.5 m) veneers over low-relief rocks of Neogene bedrock units (the Santa Cruz Mudstone and the Purisima Formation) are mapped as units Qms/Tsc and Qms/Tp?, respectively. These composite units are recognized on the basis of the combination of flat relief, continuity with moderate- to high-relief bedrock outcrops, high-resolution seismic-reflection data (see sheet 8), and (in some cases) moderate to high backscatter. Overlying sediment is interpreted as an ephemeral and dynamic sediment layer that may or may not be continuously present at a specific location, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term climate cycles. Storlazzi and others (2011) described the seasonal burial and exhumation of submerged bedrock in a similar high-energy setting in northern Monterey Bay, about 115 km south of the map area.

The southeastern part of the map area includes part of the outer flank of the horseshoe-shaped “San Francisco Bar” (unit Qmss), which has formed at the mouth of the San Francisco ebb-tidal delta (Barnard and others, 2007; Dallas and Barnard, 2011). The “San Francisco Bar” is shaped by both tidal currents and waves, the latter of which regularly exceed 6 m in height on the continental shelf during major winter storms (Barnard and others, 2007). This mix of tidal-current and wave influences has resulted in a variably hummocky, mottled, and rilled seafloor, and this surface texture is used as a primary criterion for mapping the unit and defining its boundaries.

The Offshore of Bolinas map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active faults that cumulatively form a distributed shear zone. These active faults include the San Andreas Fault, the east strand of the San Gregorio Fault Zone, the Golden Gate Fault, and the Potato Patch Fault (see sheets 8, 9; see also, Jachens and Zoback, 1999; Zoback and others, 1999; Bruns and others, 2002; Parsons and others, 2005; Ryan and others, 2008). The offshore parts of these faults, which are buried by sediment (mostly unit Qms) and, thus, have no surface expression, are mapped on the basis of seismic-reflection data (see sheet 8). The San Andreas Fault, which is the dominant plate-boundary structure, extends offshore through the southern part of the map area before moving onshore at Bolinas Lagoon. In this area, the San Andreas Fault has an estimated slip rate of 17 to 24 mm/yr (U.S. Geological Survey and California Geological Survey, 2010), and the devastating great 1906 California earthquake (M7.8) is thought to have nucleated on the San Andreas Fault offshore of San Francisco (Bolt, 1968; Lomax, 2005), a few kilometers south of the map area.

The San Andreas Fault forms the boundary between two distinct basement terranes: to the east are Jurassic and Cretaceous mélange and graywacke of the Franciscan Complex; to the west on the Point Reyes peninsula are Late Cretaceous granitic and older metamorphic rocks of the Salinian block. Rocks of the Franciscan Complex (undivided unit Kjf) form seafloor outcrops near the shoreline southeast of Stinson Beach that commonly are continuous with onshore coastal outcrops (Blake and others, 2000). Granitic rocks of the Salinian block, which crop out in the adjacent “Drakes Bay and Vicinity” map area (Watt and others, 2015), are overlain by a thick section of Neogene marine sedimentary rocks. These sedimentary rocks include the middle and upper Miocene Monterey Formation (mapped onland as unit Tm), the upper Miocene Santa Margarita Sandstone (mapped onland as unit Tsm), the upper Miocene Santa Cruz Mudstone (unit Tsc), and the upper Miocene and Pliocene Purisima Formation (unit Tp) (Clark and Brabb, 1997; Powell and others, 2007). Unit Tu consists of undivided Santa Margarita Sandstone and Santa Cruz Mudstone.

The Santa Cruz Mudstone at Bolinas is more than 1,000 m thick, measured at an oil test well (Clark and Brabb, 1997), and it forms coastal bluffs and tidal-zone exposures that extend offshore onto the adjacent, emergent bedrock shelf. The Santa Cruz Mudstone thins markedly to the northwest, and it disappears from the section about 14 km northwest of the map area (onshore of Drakes Bay) where the Purisima Formation unconformably overlies the Santa Margarita Sandstone. We infer that this angular and erosional unconformity extends offshore and southeastward into the map area, on the basis of discordant bedding and surface textures seen in the high-resolution bathymetry (see sheets 1, 2). Below the unconformity (to the northeast), rocks of the Santa Cruz Mudstone typically are more thinly bedded, forming "ribbed" outcrops, whereas above the unconformity (to the southwest), rocks inferred to be the Purisima Formation are more variably bedded and yield both "ribbed" and more massive seafloor outcrops. Both units (above and below the unconformable contact) are cut by dense, crosscutting fractures. It should be noted that this stratigraphic interpretation (the Purisima Formation unconformably overlying the Santa Cruz Mudstone in the offshore) is based on onshore outcrop trends and has not been confirmed by offshore lithologic sampling. An alternate interpretation may be that the angular unconformity is present within the Santa Cruz Mudstone, and all of the emergent rock on the Bolinas shelf belongs to that unit. We consider this alternative unlikely; to indicate this uncertainty, we have queried the Purisima Formation (unit Tp?) in the offshore part of the map area.

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

| Map Unit | Area ($m^2$) | Area ($km^2$) | Percent of total area |
|---|---|---|---|
| Marine sedimentary units | | | |
| Qms | 77,668,051 | 77.7 | 58.3 |
| Qmsc | 221,670 | 0.2 | 0.2 |
| Qmss | 3,804,006 | 3.8 | 2.9 |
| Qmsb | 1,555,870 | 1.6 | 1.2 |
| Total, sedimentary units | 83,249,598 | 83.2 | 62.5 |
| Bedrock units | | | |
| Qms/Tp? | 758,831 | 0.8 | 0.6 |
| Qms/Tsc | 845,265 | 0.8 | 0.6 |
| Tp? | 12,982,344 | 13.0 | 9.8 |
| Tsc | 33,544,713 | 33.5 | 25.2 |
| Tu | 969,457 | 1.0 | 0.7 |
| KJf | 792,921 | 0.8 | 0.6 |
| Total, bedrock units | 49,893,530 | 49.9 | 37.5 |
| Total, Offshore of Bolinas map area | 133,143,128 | 133.1 | 100.0 |

# DESCRIPTION OF MAP UNITS

## OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Note that, where older units (typically, bedrock) are overlain by thin (<1 m thick) Quaternary deposits, composite units are mapped. These composite units, which are shown with gray stipple pattern on older unit, are designated by composite label indicating both overlying sediment cover and lower (older) unit, separated by slash (for example, Qms/Tsc indicates that thin sheet of Qms overlies Tsc)]

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

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

Qmsc **Coarse-grained marine nearshore and shelf deposits (late Holocene)**—Predominantly coarse sand, gravel, and cobbles; found on gently seaward-dipping surface in three small patches south of Bolinas near California's State Waters limit; recognized primarily on basis of low relief and mottled backscatter; its presence in map area has not been verified by sampling

Qmsb **Marine ebb-tidal bar deposits (late Holocene)**—Sandy sediment that forms horseshoe-shaped bar ("San Francisco Bar") in water depths of about 8 to 12 m outside mouth of San Francisco Bay. Seafloor texture is variably hummocky and mottled, reflecting influence of both waves and tidal currents

Tp **Purisima Formation (Pliocene and late Miocene)**—Thick-bedded marine sandstone, siltstone, and mudstone, locally diatomaceous; mapped in nearshore and shelf areas west of San Andreas Fault

Tsc **Santa Cruz Mudstone (late Miocene)**—Thin- to thick-bedded siliceous mudstone; mapped in nearshore and shelf areas west of San Andreas Fault

Tu **Sedimentary rocks, undivided (late Miocene)**—May consist of the Santa Cruz Mudstone (unit Tsc) or the Santa Margarita Sandstone (mapped onland as unit Tsm)

KJf **Franciscan Complex, undivided (Cretaceous and Jurassic)**—Mostly mélange, graywacke, and shale; mapped in coastal areas east of San Andreas Fault

## ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units compiled from California Geological Survey (1974), Clark and Brabb (1997), Blake and others (2000), and Witter and others (2006); unit ages, which are from these sources, reflect local stratigraphic relations]

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

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

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

Qes **Estuarine deposits (Holocene)**—Heterogeneous mixture of coarse and fine estuarine sediment; deposited in Bolinas Lagoon

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, undivided (Holocene and late Pleistocene)**—Mapped in small valleys where separate fan, basin, and terrace deposits could not be delineated at map scale

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

Qoa **Older alluvial deposits, undivided (late Pleistocene)**—Mapped on gently sloping to level alluvial fan or terrace surfaces or where separate units could not be delineated at map scale; late Pleistocene age indicated by depth of stream incision, degree of soil development, and lack of historical flooding

Qmt **Marine-terrace deposits (Pleistocene)**—Sand and gravel; deposited on uplifted marine-abrasion platforms along coast

Qt **Stream-terrace deposits (middle and early Pleistocene)**—Sediment deposited in point-bar and overbank environments

QTm **Merced Formation (Pleistocene and Pliocene)**—Sandy siltstone, silty sandstone, and interbedded pebble conglomerate; correlative with type locality of the Merced Formation, located about 30 km to south

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

Tsm **Santa Margarita Sandstone (late Miocene)**—Massive, coarse- to fine-grained, semifriable arkosic sandstone

Tm **Monterey Formation (late and middle Miocene)**—Thin-bedded, marine porcelanite, shale, sandstone, and mudstone

**Franciscan Complex (Cretaceous and Jurassic)**—Mostly graywacke and shale; found within and east of San Andreas Fault Zone. Locally divided into following subunits:

Kfs **Sandstone and shale in San Bruno Mountain terrane (Cretaceous)**

Kfgwy **Graywacke in Nicasio Reservoir terrane (Cretaceous)**

fsr **Central Belt Mélange (Cretaceous)**

KJfch **Chert in Marin Headlands terrane (Cretaceous and Jurassic)**

Jfmg **Metamorphic rocks (Jurassic)**—Within Central Belt Mélange

Jfg **Greenstone in Nicasio Reservoir terrane (Jurassic)**

Jfgs **Greenstone in Marin Headlands terrane (Jurassic)**

**Coast Range ophiolite (Jurassic)**—Locally divided into:

sp **Serpentinite (Jurassic)**

sc **Silica-carbonate rock (Jurassic)**

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