California State Waters Map Series—Offshore of Refugio Beach, California

By Samuel Y. Johnson, Peter Dartnell, Guy R. Cochrane, Nadine E. Golden, Eleyne L. Phillips, Andrew C. Ritchie, Lisa M. Krigsman, Bryan E. Dieter, James E. Conrad, H. Gary Greene, Gordon G. Seitz, Charles A. Endris, Ray W. Sliter, Florence L. Wong, Mercedes D. Erdey, Carlos I. Gutierrez, Mary M. Yoklavich, Amy E. East, and Patrick E. Hart

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

Pamphlet to accompany

Scientific Investigations Map 3319

2015

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

Suggested citation:
Johnson, S.Y., Dartnell, P., Cochrane, G.R., Golden, N.E., Phillips, E.L., Ritchie, A.C., Krigsman, L.M., Dieter, B.E., Conrad, J.E., Greene, H.G., Seitz, G.G., Endris, C.A., Sliter, R.W., Wong, F.L., Erdey, M.D., Gutierrez, C.I., Yoklavich, M.M., East, A.E., and Hart, P.E. (S.Y. Johnson and S.A. Cochran, eds.), 2015, California State Waters Map Series—Offshore of Refugio Beach, California: U.S. Geological Survey Scientific Investigations Map 3319, pamphlet 42 p., 11 sheets, scale 1:24,000, *http://dx.doi.org/10.3133/sim3319*.

ISSN 2329-132X (online)

Contents

Figures

Tables

Map Sheets

Sheet 1. Colored Shaded-Relief Bathymetry, Offshore of Refugio Beach Map Area, California
By Peter Dartnell, Eleyne L. Phillips, and David P. Finlayson
Sheet 2. Shaded-Relief Bathymetry, Offshore of Refugio Beach Map Area, California
By Peter Dartnell, Eleyne L. Phillips, and David P. Finlayson
Sheet 3. Acoustic Backscatter, Offshore of Refugio Beach Map Area, California
By Peter Dartnell, Eleyne L. Phillips, and David P. Finlayson
Sheet 4. Data Integration and Visualization, Offshore of Refugio Beach Map Area, California
By Peter Dartnell
Sheet 5. Seafloor Character, Offshore of Refugio Beach Map Area, California
By Eleyne L. Phillips, Mercedes D. Erdey, and Guy R. Cochrane
Sheet 6. Ground-Truth Studies, Offshore of Refugio Beach Map Area, California
By Nadine E. Golden, Guy R. Cochrane, Peter Dartnell, and Lisa M. Krigsman
Sheet 7. Potential Marine Benthic Habitats, Offshore of Refugio Beach Map Area, California
By Bryan E. Dieter, H. Gary Greene, Charles A. Endris, Mercedes D. Erdey, and Nadine E. Golden
Sheet 8. Seismic-Reflection Profiles, Offshore of Refugio Beach Map Area, California
By Samuel Y. Johnson, Ray W. Sliter, James E. Conrad, Andrew C. Ritchie, Amy E. East, Patrick E. Hart, and Eleyne L. Phillips
Sheet 9. Local (Offshore of Refugio Beach Map Area) and Regional (Offshore from Refugio Beach to Hueneme Canyon) Shallow-Subsurface Geology and Structure, Santa Barbara Channel, California
By Samuel Y. Johnson, Eleyne L. Phillips, Andrew C. Ritchie, Florence L. Wong, Ray W. Sliter, Amy E. East, James E. Conrad, and Patrick E. Hart
Sheet 10. Offshore and Onshore Geology and Geomorphology, Offshore of Refugio Beach Map Area, California
By James E. Conrad, Andrew C. Ritchie, Samuel Y. Johnson, Gordon G. Seitz, and Carlos I. Gutierrez
Sheet 11. Predicted Distribution of Benthic Macro-Invertebrates, Offshore of Refugio Beach Map Area and Santa Barbara Channel Region, California
By Lisa M. Krigsman, Mary M. Yoklavich, Guy R. Cochrane, and Nadine E. Golden

California State Waters Map Series—Offshore of Refugio Beach, California

By Samuel Y. Johnson,[1] Peter Dartnell,[1] Guy R. Cochrane,[1] Nadine E. Golden,[1] Eleyne L. Phillips,[1] Andrew C. Ritchie,[1] Lisa M. Krigsman,[2] Bryan E. Dieter,[3] James E. Conrad,[1] H. Gary Greene,[3] Gordon G. Seitz,[4] Charles A. Endris,[3] Ray W. Sliter,[1] Florence L. Wong,[1] Mercedes D. Erdey,[1] Carlos I. Gutierrez,[1] Mary M. Yoklavich,[2] Amy E. East,[1] and Patrick E. Hart[1]

(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 Game, 2008), which requires information about the distribution of ecosystems as part of the design and proposal process for the establishment of Marine Protected Areas. A focus of CSMP is to map California's State Waters with consistent methods at a consistent scale.

The CSMP approach is to create highly detailed seafloor maps through collection, integration, interpretation, and visualization of swath sonar bathymetric data (the undersea equivalent of satellite remote-sensing data in terrestrial mapping), acoustic backscatter, seafloor video, seafloor photography, high-resolution seismic-reflection profiles, and bottom-sediment sampling data. The map products display seafloor morphology and character, identify potential marine benthic habitats, and illustrate both the surficial seafloor geology and shallow (to about 100 m) subsurface geology. It is emphasized that the more interpretive habitat and geology maps rely on the integration of multiple, new high-resolution datasets and that mapping at small scales would not be possible without such data.

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

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

---

[1] U.S. Geological Survey

[2] National Oceanic and Atmospheric Administration, National Marine Fisheries Services

[3] Moss Landing Marine Laboratories, Center for Habitat Studies

[4] California Geological Survey

is published as a PDF file. Geographic information system (GIS) files that contain both ESRI[5] 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 27, 2013).

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

---

[5] Environmental Systems Research Institute, Inc.

Chapter 1. Introduction

By Samuel Y. Johnson

The map area offshore of Refugio Beach, California, which is referred to herein as the “Offshore of Refugio Beach” map area (figs. 1–1, 1–2), lies within the western Santa Barbara Channel region of the Southern California Bight (see, for example, Lee and Normark, 2009). This geologically complex region forms a major biogeographic transition zone, separating the cold-temperate Oregonian province north of Point Conception from the warm-temperate California province to the south (Briggs, 1974).

The map area lies offshore of the steep, incised, south flank of the Santa Ynez Mountains. The crest of the range, which lies about 8 km from the shoreline (north of the map area), has a maximum elevation of about 780 m. The coastal zone is largely open space, partly used for livestock grazing, with no significant towns or population centers. The most significant developments are the recreational state beaches at El Capitan Beach and Refugio Beach. Highway 101 crosses the map area, adjacent to and within a few hundred meters of the shoreline.

The Offshore of Refugio Beach map area lies in the west-central part of the Santa Barbara littoral cell (fig. 1–1), which is characterized by west-to-east transport of sediment from Point Arguello on the northwest to Hueneme and Mugu Canyons on the southeast (see, for example, Griggs and others, 2005; Hapke and others, 2006). On the basis of harbor dredging records, Griggs and others (2005) reported east-southeast longshore drift rates that range from about 160,000 to 800,000 tons/yr, averaging 400,000 tons/yr. At the east end of the littoral cell, eastward-moving sediment is trapped by Hueneme and Mugu Canyons (fig. 1–1) and then transported down these canyons into the deep-water Santa Monica Basin (Normark and others, 2009).

Sediment supply to the western and central part of the littoral cell is mainly from relatively small coastal watersheds, which have an estimated cumulative annual sediment flux of 640,000 tons/yr between Point Arguello and the Ventura River (Warrick and Farnsworth, 2009). Within the Offshore of Refugio Beach map area, these coastal watersheds include (from east to west) Cañada del Capitan, Tajiquas Creek, Arroyo Hondo, Cañada del Molino, and several unnamed canyons and creeks (fig. 1–2). The much larger Santa Ynez and Santa Maria Rivers, the mouths of which are 80 to 120 km northwest of the map area, are not considered significant sediment sources because Point Conception and Point Arguello provide obstacles to southeasterly sediment transport, and much of their sediment load presently is trapped in dams (Griggs and others, 2005). Additionally, the large Ventura and Santa Clara Rivers have high sediment yields (Warrick and Farnsworth, 2009) but lie about 70 km to the southeast, “downdrift” from the map area, and, therefore, are not sediment sources for the Offshore of Refugio Beach map area. Coastal-watershed discharge and sediment load are highly variable, characterized by brief large events during major winter storms and long periods of low flow and minimal sediment load between storms. In recent history, the majority of high-discharge, high-sediment-flux events have been associated with the El Niño phase of the El Niño–Southern Oscillation (ENSO) climatic pattern (Warrick and Farnsworth, 2009).

Narrow beaches with thin sediment (sand and pebbles) cover, fronted by low (10- to 20-m-high) cliffs that are capped by a narrow coastal terrace, characterize the shoreline in the Offshore of Refugio Beach map area. Notably, a large boulder delta has formed at El Capitan Beach by deposition from Cañada del Capitan Creek (Griggs and others, 2005). Beaches are subject to wave erosion during winter storms, followed by gradual sediment recovery or accretion during the late spring, summer, and fall months during the gentler wave climate. Hapke and others (2006) suggested that essentially no net change (accretion or erosion) to the beaches in the map area has occurred over the long term (since the mid- to late 1800s); however, the beaches have been eroding at an average rate of about 0.6 m/yr over the short term (1976 to 1998). Hapke and Reid (2007) also indicated that coastal bluffs in the map area are eroding at a rate of about 0.2 m/yr. As with stream discharge and sediment flux, coastal erosion has been most acute during the El Niño phases of the ENSO climatic pattern.

The Offshore of Refugio Beach map area consists of relatively flat and shallow continental shelf. The shelf dips gently seaward (about 0.8° to 1.0°), and water depths at the 3-nautical-mile (5.6-km) limit of California's State Waters range from about 80 to 100 m. Locally, slopes are steeper (about 2° to 3°) in relatively shallow water (10 to 30 m) on the seaward-facing slope of nearshore bars (fig. 1–2, see also, sheets 1, 2). This part of the Southern California Bight is relatively well protected from large Pacific swells from the north and northwest by Point Conception and from south and southwest swells by offshore islands and banks (O'Reilly and Guza, 1993). Fair-weather wave base is typically shallower than 20-m water depth, but winter storms are capable of resuspending fine-grained sediments in 30 m of water (Xu and Noble, 2009, their table 7), and so shallow (depths of 30 to 60 m) shelf sediments in the map area probably are remobilized on an annual basis. As with sediment discharge from rivers, the largest wave events and the highest sediment transport rates on the shelf are typically associated with ENSO events. The shelf is underlain by bedrock and variable amounts (0 to 12 m) of upper Quaternary shelf, estuarine, and fluvial sediments deposited as sea level fluctuated in the late Pleistocene (see Sheet 9 of this report; see also, Slater and others, 2002; Draut and others, 2009).

In the map area, the shelf break is at depths of about 90 m and lies about 5.6 to 6.4 km offshore. Beyond the shelf break, the slope is steep (as much as about 7°) and unstable. Several submarine landslides have been documented offshore of Goleta, a few kilometers east of the map area (Fisher and others, 2005; Greene and others, 2006; Lee and others, 2009). One of the largest slides (about 130 km^2) is the Goleta landslide complex (fig. 1–1), which is inferred to have been initiated more than 200,000 year ago but which also includes three recent failure thought to have been generated 8,000 to 10,000 years ago (Greene and others, 2006); in addition, smaller slides may have occurred as recently as 300 years ago (Lee and others, 2009). Modeling of the larger events indicates that they could have generated a local, 10-m-high tsunami (Greene and others, 2006).

Seafloor habitats in the broad Santa Barbara Channel region consist of significant amounts of soft, unconsolidated sediment interspersed with isolated areas of rocky habitat that support kelp-forest communities nearshore and rocky-reef communities in deep water. The potential marine benthic habitat types mapped in the Offshore of Refugio Beach map area are directly related to its Quaternary geologic history, geomorphology, and active sedimentary processes. These potential habitats lie primarily within the Shelf (continental shelf) but also partly within the Flank (basin flank or continental slope) megahabitats of Greene and others (2007). The fairly homogeneous seafloor of sediment and low-relief bedrock provides characteristic habitat for groundfish, crabs, shrimp, and other marine benthic organisms. The bedrock outcrops are potential benthic habitats for rockfish (*Sebastes* spp.) and other groundfish that forage and seek refuge in such habitats. In addition, several areas of smooth sediment that form nearshore terraces with relatively steep, smooth fronts may provide interfaces attractive to certain species of groundfish. Below the steep shelf break, within the basin flank or continental slope megahabitat, the seafloor is composed of soft sediment interrupted by a few carbonate mounds, some bedrock exposures, and a gully. Carbonate mounds and the steep shelf break also are good potential habitat for rockfish.

The Offshore of Refugio Beach map area is in the Ventura Basin, in the southern part of the Western Transverse Ranges geologic province, which is north of the California Continental Borderland[6] (Fisher and others, 2009). Significant clockwise rotation—at least 90°—since the early Miocene has been proposed for the Western Transverse Ranges province (Luyendyk and others, 1980; Hornafius and others, 1986; Nicholson and others, 1994), and this region is presently undergoing north-south

---

[6] The California Continental Borderland is defined as the complex continental margin that extends from Point Conception south into northern Baja California.

shortening (see, for example, Larson and Webb, 1992). Regional cross sections (Tennyson and Kropp, 1998; Forman and Redin, 2005; Redin, 2005) suggest that the south flank of the Santa Ynez Mountains is a large, south-dipping homocline that extends beneath the continental shelf. The homoclinal section extends upward from the Cretaceous strata exposed high in the mountains to the Pliocene strata encountered at shallow depths in offshore wells. Coastal cliffs mainly consist of fine-grained, folded strata of the early Miocene Rincon Shale, the Miocene Monterey Formation, and the late Miocene and early Pliocene Sisquoc Formation (Dibblee, 1981a,b). Uplift rates in the map area, which are based on marine-terrace elevations and geochronology, are estimated to be about 0.25 to 0.5 mm/yr (Muhs and others, 1992; Metcalf, 1994).

Smaller folds (see sheets 8, 9, 10) related to local faulting are superimposed on the regional homocline. One of these superimposed anticlines hosts the Molino gas field, which was discovered in 1962 and subsequently developed through directional drilling from onshore wells (Galloway, 1998). The Oligocene Sespe and Vaqueros Formations are the reservoirs in the Molino gas field (Forman and Redin, 2005), and the map area includes numerous seafloor hydrocarbon seeps (Ashley and others, 1977).

Publication Summary

This publication about the Offshore of Refugio Beach map area includes eleven 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 two 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 Santa Barbara shelf interspersed with tectonically controlled bedrock uplifts and coarse-grained deltas and sediment lobes associated with coastal watersheds. To validate the geological and biological interpretations of the sonar data shown on 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, and rugosity (ruggedness), and backscatter intensity and which is further informed by 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 Santa Barbara region (offshore from Refugio Beach to Hueneme Canyon), interpretated 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). Sheet 11 uses the ground-truth-survey imagery to develop a statistical model and maps that predict the distribution of benthic macro-invertebrates for both the Offshore of Refugio Beach map area and the Santa Barbara Channel region.

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, habitat mapping, and maps of predicted species distribution 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 development of regional sediment-management plans. Documentation of hydrocarbon seepage and tarball accumulation is critical for distinguishing “natural” from anthropogenic pollution. In addition, citing of any new offshore infrastructure (for example, pipelines, cables, or renewable-energy facilities) will depend on new 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.

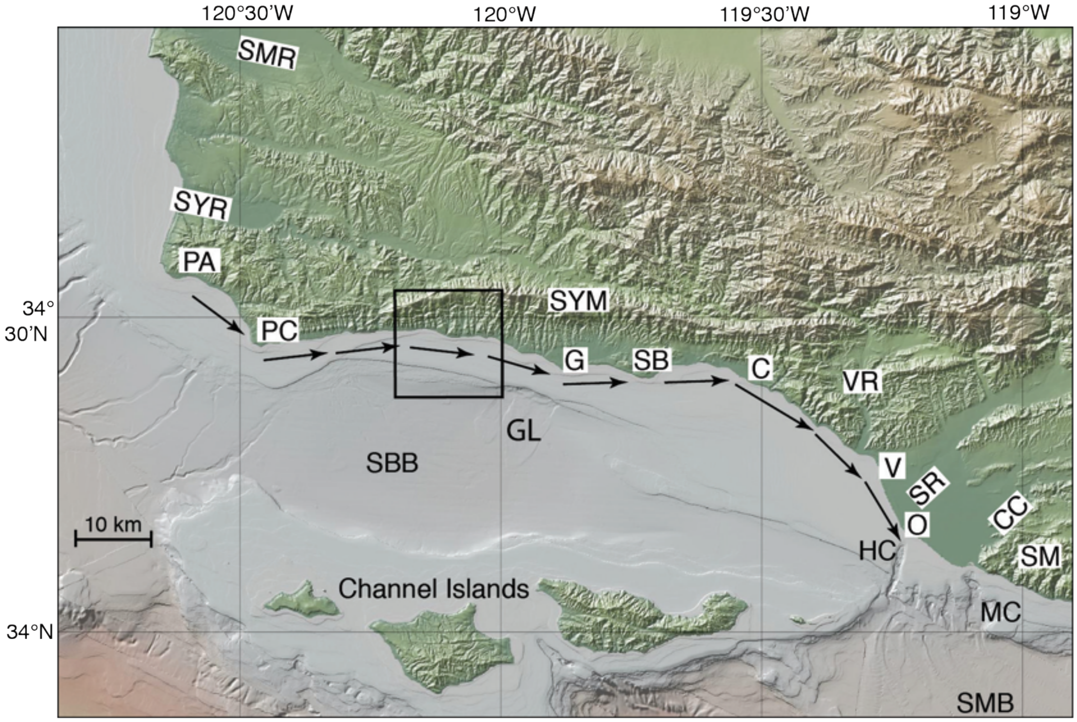

Figure 1–1. Physiography of Santa Barbara Channel region. Box shows Offshore of Refugio Beach map area. Arrows show direction of sediment transport in Santa Barbara littoral cell, which extends from Point Arguello (PA) to Hueneme Canyon (HC) and Mugu Canyon (MC). Other abbreviations: C, Carpinteria; CC, Calleguas Creek; G, Goleta; GL, Goleta slide; O, Oxnard; PC, Point Conception; SB, Santa Barbara; SBB, Santa Barbara Basin; SM, Santa Monica Mountains; SMB, Santa Monica Basin; SMR, Santa Maria River; SR, Santa Clara River; SYM, Santa Ynez Mountains; SYR, Santa Ynez River; V, Ventura; VR, Ventura River.

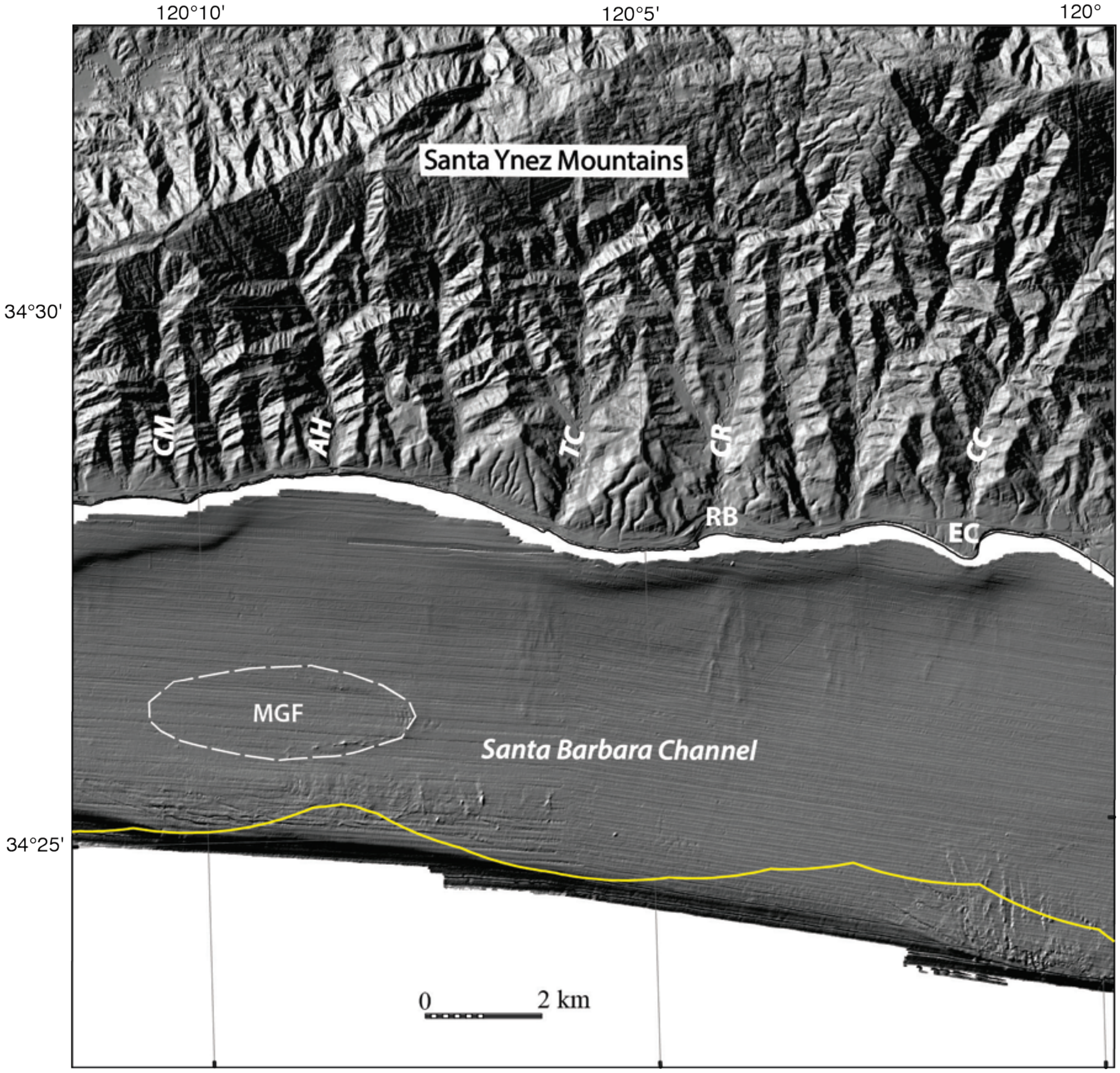

Figure 1–2. Coastal geography of Offshore of Refugio Beach map area. Dashed line shows boundary of Molino gas field (MGF) (from Barnum, 1998). Other abbreviations: AH, Arroyo Hondo; CC, Cañada del Capitan and El Capitan Creek; CM, Cañada del Molino; CR, Cañada del Refugio; EC, El Capitan Beach; RB, Refugio Beach; TC, Tajiquas Creek. Yellow line is 3-nautical-mile limit of California's State Waters.

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

By Peter Dartnell

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of Refugio Beach map area in southern California were generated from bathymetry and backscatter data collected by the U.S. Geological Survey (USGS) and by Fugro Pelagos for the U.S. Army Corps of Engineers (USACE) Joint Lidar Bathymetry Technical Center of Expertise (fig. 1 on sheets 1, 2, 3). The offshore area was mapped by the USGS in 2008, using a 234.5-kHz SEA (AP) Ltd. SWATHplus-M phase-differencing sidescan sonar. The nearshore bathymetry and coastal topography were mapped for USACE by Fugro Pelagos in 2009, using the SHOALS-1000T bathymetric-lidar and Leica ALS60 topographic-lidar systems. These mapping missions combined to collect bathymetry (sheets 1, 2) from the 0-m isobath to beyond the 3-nautical-mile limit of California's State Waters, as well as acoustic-backscatter data (sheet 3) from about the 10-m isobath to beyond the 3-nautical-mile limit.

During the USGS mapping mission, GPS data with real-time-kinematic corrections were combined with measurements of vessel motion (heave, pitch, and roll) in a CodaOctopus F180 attitude-and-position system to produce a high-precision vessel-attitude packet. This packet was transmitted to the acquisition software in real time and combined with instantaneous sound-velocity measurements at the transducer head before each ping. The returned samples were projected to the seafloor using a ray-tracing algorithm that works with previously measured sound-velocity profiles. Statistical filters were applied to discriminate seafloor returns (soundings and backscatter intensity) 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 geographic information system (GIS) and converted to GRIDs.

During the 2009 Fugro Pelagos coastal airborne-lidar mapping mission that was completed as part of the National Coastal Mapping Program of USACE, the Leica ALS60 topographic-lidar and the SHOALS-1000T bathymetric-lidar systems were mounted on an aircraft that flew survey lines at an altitude of 300 to 400 m (bathymetry) and 300 to 1,200 m (topography), at speeds of between 135 and 185 knots. The ALS60 system collected data at a maximum pulse rate of 200 kHz, and the SHOALS system collected data at 1 kHz. Information on aircraft position, velocity, and acceleration were collected using the Novatel and POS A/V 410 systems (SHOALS) and the onboard GPS/IMU system (ALS60). Aircraft-position data were processed using POSPac software, and the results were combined with the lidar data to produce 3-D positions for each lidar shot. Various commercial and proprietary software packages were used to clean the data, to convert all valid data from ellipsoid to orthometric heights, and to export the data as a series of topography and bathymetry ASCII files.

Soundings from the different mapping missions were converted into individual 2-m-resolution bathymetric-surface-model grids. The individual bathymetric-surface models were then merged into one overall bathymetric-surface model and clipped to the boundary of the map area. Difference calculations of the overlapping bathymetry grids showed that there is good agreement between surveys (mean difference of 0.15 m, standard deviation of 0.27), even though the surveys were conducted at different times using different mapping equipment, and in the dynamic nearshore environment.

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 Refugio Beach 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, 10) were generated from a modified bathymetric surface of California's State Waters within the Santa Barbara Channel. This surface was generated by merging all of California Seafloor Mapping Program's bathymetry data for the region into one surface model. After merging, the surface model was resampled to 10-m resolution, and then a smooth arithmetic mean convolution function that assigns a weight of one-ninth to each cell in a 3-pixel by 3-pixel matrix was applied iteratively to the surface ten times. Following smoothing, contour lines were generated at 10-m intervals from -10 to -100 m and then clipped to the boundary of the map area.

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

The onshore-area image was generated by applying an illumination having an azimuth of 300° and from 45° above the horizon to the coastal airborne topographic-lidar data, as well as to publicly available, 3-m-resolution, interferometric synthetic aperture radar (ifSAR) data, available from National Oceanic and Atmospheric Administration (NOAA) Coastal Service Center's Digital Coast (National Oceanic and Atmospheric Administration, 2011).

Chapter 3. Data Integration and Visualization for the Offshore of Refugio Beach 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 Refugio Beach 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 Refugio Beach 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 greens 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, 2, 4, 5, and 6 on sheet 4. These views highlight the relatively low-relief, natural outcrops along the outer shelf in the Offshore of Refugio Beach map area, as well as sediment-transport features within the nearshore area.

Video-mosaic images created from digital seafloor video (for example, fig. 3 on sheet 4) display the geologic complexity (rock, sand, and mud; see sheet 10) and biologic complexity (see sheet 11) 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 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 (Sliter and others, 2008) 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 Refugio Beach Map Area (Sheet 5)

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

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

The following four substrate classes are identified in the Offshore of Refugio Beach 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: Anthropogenic material (rugged)

The seafloor-character map of the Offshore of Refugio Beach map area (sheet 5) was produced using video-supervised maximum-likelihood classification of the bathymetry and intensity of return from sonar systems, following the method described by Cochrane (2008). The two variants used in this classification were backscatter intensity and derivative rugosity, which is a standard calculation performed with the National Oceanic and Atmospheric Administration (NOAA) benthic-terrain modeler (available at http://www.csc.noaa.gov/digitalcoast/tools/btm/index.html; last accessed March 4, 2013), using a 3-pixel by 3-pixel array of bathymetry.

Classes I, II, and III values were delineated using multivariate analysis. Class IV (rugged anthropogenic material related to oil pipeline) values were determined on the basis of their visual characteristics and the known location of man-made features. The resulting maps were 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 Refugio Beach map area, only Depth Zones 2, 3, and 4 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 Refugio Beach map area, only Slope Classes 1 and 2 are present. The final classified seafloor-character raster map image is draped over the shaded-relief bathymetry for the area (sheets 1 and 2) to produce the image shown on the seafloor-character map on sheet 5.

The seafloor-character classification is also summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 91.2 percent (104.3 km^2) of the map area: 11.3 percent (12.9 km^2) is in Depth Zone 2, 79.3 percent (90.7 km^2) is in Depth Zone 3, and 0.6 percent (0.7 km^2) is in Depth Zone 4. 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 8.5 percent (9.7 km^2) of the map area: 0.4 percent (0.5 km^2) is in Depth Zone 2, 3.9 percent (4.5 km^2) is in Depth Zone 3, and 4.1 percent (4.7 km^2) is in Depth Zone 4. Rock and boulder, rugose (rock outcrops and boulder fields having high surficial complexity) makes up 0.1 percent (0.2 km^2) of the map area: less than 0.1 percent (<0.1 km^2) is in Depth Zone 2, 0.1 percent (0.2 km^2) is in Depth Zone 3, and less than 0.1 percent (<0.1 km^2) is in Depth Zone 4. Rugged anthropogenic material (a pipe that traverses the entire width of California's State Waters in the map area) makes up 0.2 percent (0.2 km^2) of the map area: less than 0.1 percent (<0.1 km^2) is in Depth Zone 2, 0.2 percent (0.2 km^2) is in Depth Zone 3, and less than 0.1 percent (<0.1 km^2) is in Depth Zone 4.

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 determined from the visual characteristics and known locations of man-made features.

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 4–1 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 4–1 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 Refugio Beach map area is mainly flat, with small, local sedimentary-bedrock exposures (Class III) on the outer shelf and slope. The seabed is predominantly covered by Class I sediment composed of soft, unconsolidated sand and mud. Class II sediments varies from gravel to sediment-covered tar flows. Differentially eroded sedimentary-bedrock outcrops (Class

III) are present mainly further offshore on the outer shelf and slope, including outcrops near and just outside the 3-nautical-mile limit of California's State Waters. Exposed rock is covered intermittently by varying thicknesses of fine- (Class I) to coarse-grained (Class II) sediment (coarse sand and gravel). One rugged anthropogenic feature (Class IV), an oil pipeline, cuts across both the shelf and slope.

The classification accuracy of Classes I and II (81 and 62 percent accurate, respectively; table 4–2) is determined by sediments are found to be accurate based on comparing the shipboard video observations and the classified map. The weaker (10 percent) agreement in Class III likely is due to the distribution of small, localized rock outcrops and also the relatively narrow, intermittent nature of transition zones from sediment to rock, as well as the size of the buffer. The bedrock outcrops in this area are composed of sedimentary rocks exhibiting differential erosion (Cochrane and Lafferty, 2002). Erosion of softer layers produces Class I and II sediments, resulting in patchy rugose rock and boulder habitat on the seafloor. A single buffered observation locale of 78 pixels, therefore, is likely to be interspersed with other classes of pixels, as well as with 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. Within the coverage of the 2-m-resolution seafloor-character map, the presence/absence accuracy was found to be significant for Classes I and II (88 percent for Class I, and 73 percent for Class II). Only a limited number of observations (16 total) were made over Class III rugose rock and boulder substrate, likely because the rock outcrops in the map area are characterized by linear, narrow ridges; therefore, the presence/absence is somewhat lower (25 percent) for Class III. Even though the pipe was observed on the video footage, it was not part of the 10-second period used for recording the sediment type therefore no video observations were available for accuracy assessment of Class IV substrate.

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 Refugio Beach 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	cobbles	low	
mud	gravel	low	
mud	sand	low	
mud	mud	low	
sand	mud	low	
sand	sand	low	
			sediment
			ripples
Class II			
cobbles	mud	low	
mud	rock	low	
mud	boulders	low	
mud	boulders	moderate	
rock	mud	low	
rock	sand	low	
Class III			
boulders	cobbles	moderate	
boulders	mud	moderate	
boulders	sand	moderate	
cobbles	rock	moderate	
rock	boulders	moderate	
rock	cobbles	high	
rock	mud	moderate	
rock	rock	moderate	

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

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

Class	Number of observations	% majority	% presence/absence
I—Fine- to medium-grained smooth sediment	342	80.9	88.0
II—Mixed smooth sediment and rock	22	62.4	72.7
III—Rock and boulder, rugose	16	10.3	25.0
IV—Rugged anthropogenic feature (pipe)	0	N/A	N/A

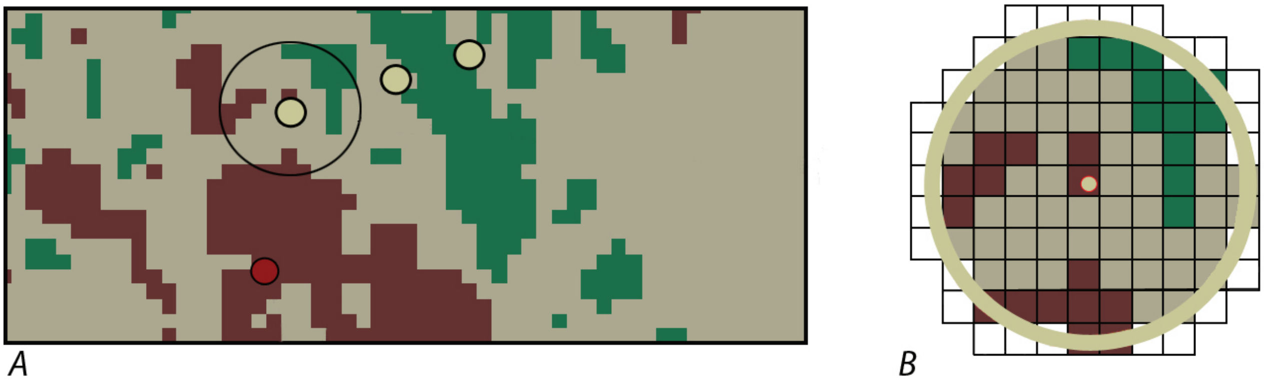

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

Chapter 5. Ground-Truth Studies for the Offshore of Refugio Beach 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 Refugio Beach map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred on two separate cruises in 2007 and 2008. The camera sled was towed 1 to 2 m above the seafloor, at speeds between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 7.85 trackline kilometers of video and 838 still photographs, in addition to 457 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

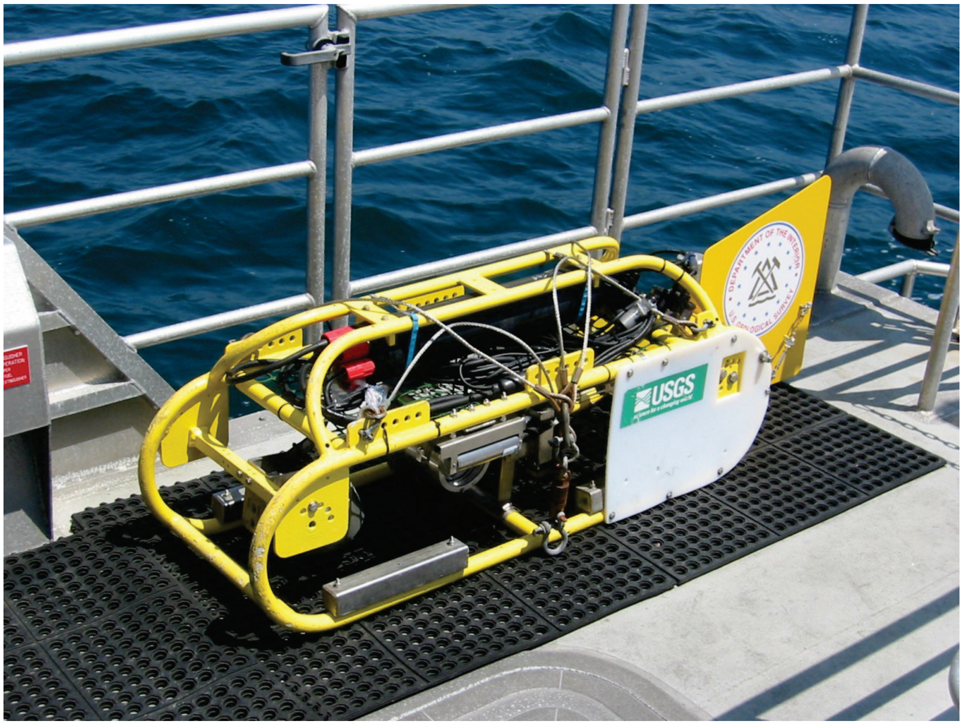

Figure 5–1. Photograph of camera sled used in USGS 2008 ground-truth survey.

During the 2008 cruise, a USGS 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 are also made.

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

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

The ground-truth survey is designed to investigate areas that represent the full spectrum of high-resolution multibeam bathymetry and backscatter-intensity variation. Figure 5–2 shows that, in the Offshore of Refugio Beach map area, the seafloor surface is covered predominantly by sediment with two areas of low-relief rock outcrops toward the edge of the shelf. The seafloor in both areas consists of mixed sediment and rock, as well as flat rock outcrops.

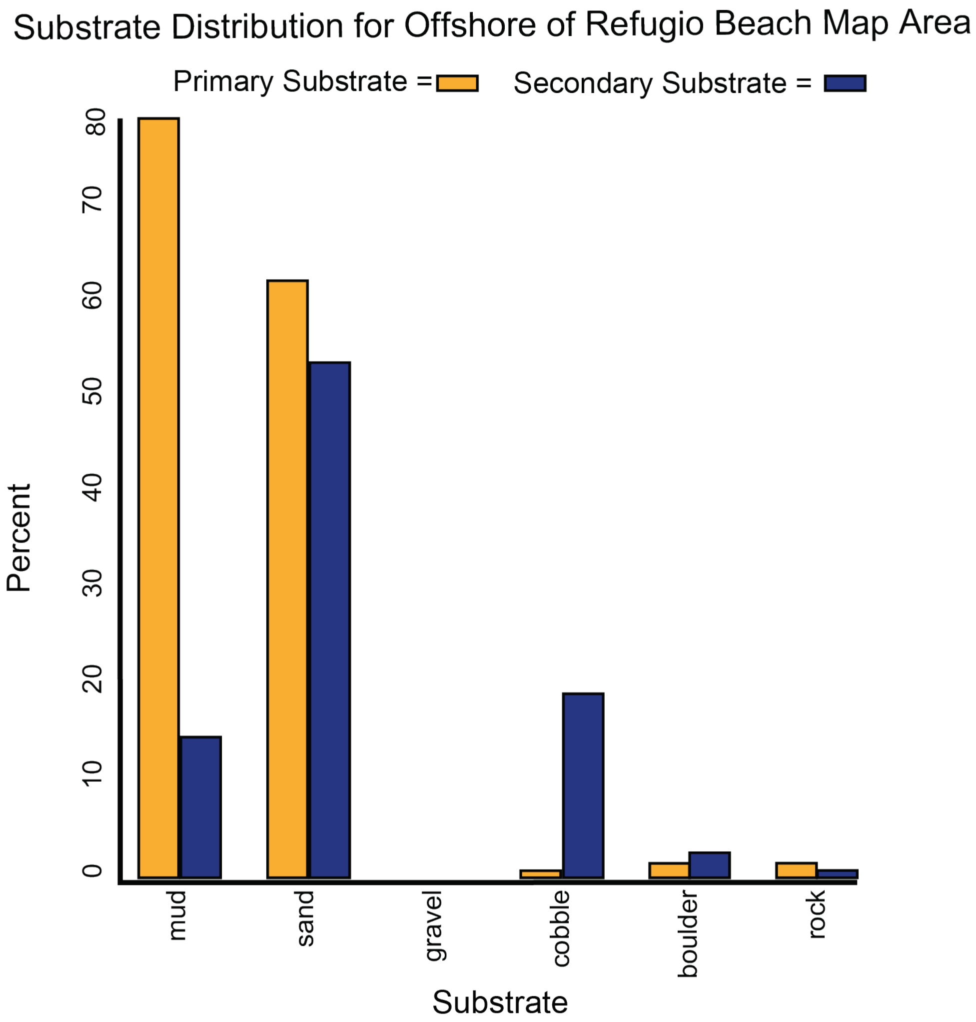

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Refugio Beach map area.

Chapter 6. Potential Marine Benthic Habitat Map of the Offshore of Refugio Beach Map Area (Sheet 7)

By H. Gary Greene and Charles A. Endris

The map on sheet 7 shows “potential” marine benthic habitats of the Offshore of Refugio Beach 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 Refugio Beach map area. High-resolution sonar bathymetry data, converted to depth grids (seafloor DEMs; sheet 1), are essential to development of the potential marine benthic habitat map, as is shaded-relief imagery (sheet 2), which allows visualization of seafloor terrain and provides a foundation for interpretation of submarine landforms.

Backscatter maps (sheet 3) are also essential for developing potential benthic habitat maps. High backscatter is further indication of “hard” bottom, consistent with interpretation as rock or coarse sediment. Low backscatter, indicative of a “soft” bottom, generally indicates a fine sediment environment. Habitat interpretations are also 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 (sheets 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 Refugio Beach 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 six categories and their attribute codes that are used on the Offshore of Refugio Beach 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.

F = Flank; continental slope, basin and (or) island flanks (200 to 3,000 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
(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
c = Canyon
    c(b) = Bar within thalweg
    c(c) = Curve or meander within thalweg
    c(f) = Fall or chute within thalweg
    c(h) = Canyon head
    c(m) = Canyon mouth
    c(t) = Thalweg
    c(w) = Canyon wall
d = Deformed, tilted and (or) folded bedrock; overhang
e = Exposure; bedrock
f = Flat; floor
g = Gully; channel
h = Hole; depression
l = Landslide; mass movement; rubble
m = Mound; linear ridge
o = Overbank deposit; levee
p = Pinnacle; cone
r = Rill (linear depression on surface formed by subterranean winnowing of sediment)
s = Scarp, cliff, fault, or slump scar
t = Terrace

v = Vegetated (grass- or algae-covered) sediment or rock
w = Dynamic bedform
  w(w) = Sediment wave (amplitude, 10 cm to a meter; wave length, tens of meters)
  w(d) = Sediment dune (amplitude, tens of meters; wave length, hundreds of meters)
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 a hyphen or in parentheses (or both), following an underscore; multiple attributes separated by slash.

_a = Anthropogenic (artificial reef, breakwall, shipwreck, disturbance)
  _a-c = Cable
  _a-dd = Dredge disturbance
  _a-dg = Dredge groove or channel
  _a-dp = Dredge potholes
  _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-m = Marina, harbor
  _a-p = Pipeline
  _a-s = Support; dock piling, dolphin
  _a-td = Trawl disturbance
  _a-w = Wreck, ship, barge, or plane
_b = Bimodal (conglomeratic, mixed [gravel, cobbles, and pebbles])
_c = Consolidated sediment (claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
_d = Differentially eroded
_e = Effusive pit; pockmark
_f = Fracture, joint; faulted
_g = Granite
_h = Hummocky, irregular relief
_i = Interface; lithologic contact
_k = Kelp
_l = Limestone or carbonate rock or structure
  _l(a) = Alive reef
  _l(d) = Dead reef
  _l(l) = Linear reef
  _l(p) = Patch reef
  _l(pr-a) = Aggregated patch reef
  _l(pr-i) = Individual patch reef
  _l(r) = Reef rubble
  _l(s-g) = Spur and groove
_m = Massive sedimentary bedrock
_o = Outwash
_p = Pavement
_r = Ripple (amplitude, greater than 10 cm)
_s = Scour (current or ice; direction noted)
_u = Unconsolidated sediment
_v = Volcanic rock

_w = Wall

Seafloor Slope—Denotes slope, typically calculated from XYZ high-resolution bathymetry data. Depicted on map by number, listed after modifier.

1 = Flat (0º–5º)
2 = Sloping (5º–30º)
3 = Steeply sloping (30º–45º)
4 = Vertical or near vertical (45º–90º)
5 = Overhanging (more than 90º)
6 = Unknown

Geologic Attribute—Describes additional geologic features seen in video, still photographs, or other types of direct observations. Depicted on map by lower-case letter(s) in parentheses, preceded by an asterisk.

*(a) = Anthropogenic (for example, cable, pipeline, disturbance)
    *(a-d) = Dredge track, pit, or mound
*(b) = Boulder
*(d) = Deformed, faulted, or folded
*(e) = Exposure, bedrock (sedimentary, igneous, or metamorphic)
    *(e-r) = Rough bedrock surface
*(f) = Fan or apron
*(g) = Gravel
*(j) = Joint, crack, crevice, overhang (differentially eroded)
*(l) = Limestone, carbonate deposit
*(m) = Mud, silt, or clay
*(q) = Coquina (shell hash)
*(r) = Rubble
*(s) = Sand
*(t) = Flat, terracelike seafloor, including sedimentary pavement
*(u) = Undulating surface, hummocky
    *(u-r) = Ripple
    *(u-s) = Scour
    *(u-w) = Sediment wave
*(y) = Barnacle or plate

Examples of Attribute Coding

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

Ssc(h)_u2/4 = Canyon head that indents shelf and has smooth, soft, gently sloping, sedimentary walls, locally cropping out as steep (near vertical) scarps (10 to 100 m).

Ssf_u1 = Flat to gently sloping shelf that has soft, unconsolidated sediment (10 to 150 m).

Fhe_m/c = Continental slope that has hard sedimentary (sandstone) bedrock exposures locally and smooth to moderately irregular relief (less than 1 m to 3 m high); exposures often covered with sediment (200 to 2,500 m).

Ssm_a/u*(q) = Soft, unconsolidated sediment and shell-hash mound, adjacent to oil platform (anthropogenic).

Map Area Habitats

Delineated in the Offshore of Refugio Beach map area are 16 potential marine benthic habitat types within two megahabitat settings, “Shelf” (continental shelf) and “Flank” (basin flank or continental slope). On the shelf, these habitat types range from predominantly soft, unconsolidated sediment (sand and mud) to areas of hard bedrock exposures (differentially eroded, well-bedded sedimentary outcrops). Some sedimentary-bedrock outcrops are partly covered with sediment to produce a hard-soft mixed habitat type. Pockmarks and carbonate mounds complete the variety of habitats identified on the continental shelf. Minor anthropogenic features associated with oil production, such as pipelines, cut across both the shelf and slope. The narrow band of basin-flank or continental-slope megahabitat that has been mapped contains macro- and mesohabitats of predominantly soft, unconsolidated sediment that has some well-layered sedimentary bedrock and carbonate mounds exposed. Along the distal edge of the continental shelf, stringers and mounds of carbonate outcrops provide good potential habitat for rockfish (*Sebastes* spp.), lingcod (*Ophiodon elongatus*), and other demersal fish.

The soft, unconsolidated sediment habitat on the continental shelf, which includes pockmarks and nearshore bars, covers 86.9 km^2 of the map area, representing 75.8 percent of all the potential habitat types identified. Sediment-covered bedrock on the continental shelf, which includes the hard-soft mixed habitat type, covers 17.5 km^2 (15.2 percent). Hard bedrock exposures on the continental shelf cover 2.6 km^2 (2.3 percent). Mixed substrate on the continental slope covers 2.3 km^2 (2 percent). Unconsolidated soft sediment on the continental slope covers 4.9 km^2 (4.3 percent) and hard bedrock exposures, including carbonate mounds, at the top of the continental slope cover 0.16 km^2 (0.1 percent). Anthropogenic features on both the shelf and slope cover nearly 0.23 km^2 (0.2 percent).

Fluid flowing up to the seafloor from petroleum reservoirs at depth has resulted in the formation of locally exposed, hard, carbonate mounds and pockmarks. These carbonate mounds and hard rock are locally covered with sediment, providing potential habitat for sessile organisms. Sedimentary-bedrock exposures in the nearshore provide hard, irregular substrate for rockfish and other groundfish habitat. This mix of potential marine benthic habitat types provides the varied relief, rugosity, and substrate hardness that contribute to the concentration of a diverse marine ecosystem within an otherwise homogeneous, soft, unconsolidated sediment habitat.

Chapter 7. Subsurface Geology and Structure of the Offshore of Refugio Beach Map Area and the Santa Barbara Channel Region (Sheets 8 and 9)

By Samuel Y. Johnson, James E. Conrad, Eleyne Phillips, Andrew Ritchie, Florence L. Wong, Ray W. Sliter, Amy E. East, and Patrick E. Hart

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 Refugio Beach map area. These profiles, which are collected at several resolutions, extend to varying depths in the subsurface, depending on the purpose and mode of data acquisition. The seismic-reflection profiles (sheet 8) provide information on sediment character, distribution, and thickness, as well as potential geologic hazards, including active faults, areas prone to strong ground motion, and tsunamigenic slope failures. The information on faults provides essential input to national and state earthquake-hazard maps and assessments (see, for example, Petersen and others, 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 Heck, 1998; Minor and others, 2009; Jennings and Bryant, 2010; Southern California Earthquake Data Center, 2010).

Data Acquisition

Most profiles displayed on sheet 8 (figs. 1, 3, 5, 6, 7, 8, 9, 10) were collected in 2008 on U.S. Geological Survey (USGS) cruise S–7–08–SC (Sliter and others, 2008). Single-channel seismic-reflection data were acquired using the EdgeTech 512 chirp subbottom-profiling system consisting of a source transducer housed in a 500-lb fish towed at a depth of several meters below the sea surface. The swept-frequency chirp source signal was 500 to 4,500 Hz and 50 ms in length, and it was recorded by hydrophones located on the bottom of the fish. 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. 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.

Figures 2 and 4 on sheet 8 show deep-penetration, migrated, multichannel seismic-reflection profiles collected in 1985 by WesternGeco on cruise W–40–85–SC. These profiles and other similar data were collected in many areas offshore of California in the 1970s and 1980s when these areas were considered a frontier for oil and gas exploration. Much of these data have been publicly released and are now archived at the U.S. Geological Survey National Archive of Marine Seismic Surveys (U.S. Geological Survey, 2009). These data were acquired using a large-volume air-gun source that has a frequency range of 3 to 40 Hz and recorded with a multichannel hydrophone streamer about 2 km long. Shot spacing was about 30 m. These data can resolve geologic features that are 20 to 30 m thick, down to subbottom depths of about 4 km.

Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Refugio Beach map area that document a relatively flat (less than 1°), moderately deep (less than 80 m) wave-cut shelf. This shelf is underlain by variably thick (0 to about 15 m; mean thickness, 2.7 m) upper Pleistocene and Holocene marine, deltaic, and alluvial sediments (Draut and others, 2009; Sommerfield and others, 2009) deposited in the last about 21,000 years during the about 125-m sea-level rise that followed glaciation and the last major sea-level lowstand. Sea-level rise after the Last Glacial Maximum (LGM) was rapid (about 10 to 11 m per thousand years) until about 7,000 years ago, at which time it slowed considerably (to about 1 m per thousand years) (Fairbanks, 1989; Fleming and others, 1998; Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006). Local relief on the shelf is associated with bedrock uplifts (sheet 10).

In the high-resolution seismic-reflection profiles on sheet 8 (figs. 1, 3, 5, 6, 7, 8, 9, 10), the sediments deposited during this post-LGM sea-level rise (shaded blue in profiles on sheet 8) commonly are "acoustically transparent," that is, lacking internal reflections. The presence and continuity of seismic reflections in this upper, post-LGM unit on many profiles is also obscured by interstitial gas within the sediment. This effect has been referred to as "gas blanking," "acoustic turbidity," or "acoustic masking" (Hovland and Judd, 1988; Fader, 1997). The gas scatters or attenuates the acoustic energy, preventing penetration. Not surprisingly, this effect is especially prevalent near the Molino gas field (see, for example, Kunitomi and others, 1998) and near the crests of other anticlines.

Because the shelf was partly emergent during the postglacial period of rising sea level, the lower part of the post-LGM unit may, in places (especially where the unit is thickest), consist of alluvial plain and estuarine deposits. These nonmarine to marginal-marine strata were covered by nearshore and shelf sediments as sea level rose and the shoreline migrated both landward and upward. The upper part of this unit likely consists of a mix of shelf and deltaic deposits that are similar to the sediment being deposited on the shelf today (see sheet 6).

On most profiles on sheet 8, the base of the post-LGM depositional unit is a flat to concave angular unconformity, characterized by an obvious change in reflectivity. The post-LGM unit commonly thins or pinches out over local uplifts (for example, figs. 7, 8). Sediment-covered wave-cut platforms and risers (see, for example, Kern, 1977) are imaged at the base of the unit on some profiles most commonly at depths of about 71 m, 50 m, and 41 m (see, for example, figs. 1, 7, 8). Given uplift rates from nearby coastal terraces (about 0.3 to 0.5 m/ka; Muhs and others, 1992), these depths are most consistent with formation during the post-LGM transgression. Post-LGM sea-level rise and landward shoreline migration were not steady but, rather, were characterized by periods of relative stability and rapid submergence (see, for example, Peltier, 2005; Stanford and others, 2011). For example, sea level rose about 20 m in 200 to 500 years during meltwater pulse 1a, about 14,000 years ago (Stanford and others, 2011). Such pulses rapidly submerge wave-cut platforms, shorelines, and shoreline angles (Kern, 1977), thereby increasing the potential for their preservation. The shallower submerged shoreline angles and platforms could have a similar post-LGM origin, or they could have formed at similar sea-level stands earlier in the late Pleistocene (for example, Wright, 2000).

Geologic Structure and Recent Deformation

High-resolution seismic-reflection profiles in the Offshore of Refugio Beach map area (sheet 8) primarily show south-dipping Neogene strata within a large homocline that extends from the south flank of the Santa Ynez Mountains (fig. 1–2) into the offshore. Regional cross sections (Tennyson and Kropp, 1998; Forman and Redin, 2005; Redin, 2005) and industry seismic-reflection profiles (figs. 2, 4 on sheet 8) indicate that the homocline formed above the blind North Channel Fault. The fault tip is inferred to be buried about 2 km deep (about 1.5 sec TWT), about 5 to 6 km offshore, beneath the upper slope and just outside California's State Waters.

The North Channel Fault Zone is inferred to include several splays that are structurally above the main fault, on the basis on the irregular pattern of shallow folds in the map area. Closely spaced seismic-reflection profiles reveal that these shallow folds display variable geometry, length, amplitude, continuity, and wavelength (see sheets 8, 10). Smaller scale, variably continuous folds that have wavelengths of about 300 to 1,000 m (for example, figs. 3, 5 on sheet 8) are superimposed on the larger homocline. The most notable of these smaller scale folds is the anticline that hosts the Molino gas field in the southwestern part of the map area (fig. 1–2). This anticlinal trend appears to be truncated to the east by an east-northeast-striking fault (fig. 5 on sheet 8; see also, sheet 10).

Ashley and others (1977) extended the east-west-striking (~270°) Eagle Fault (mapped onland by Dibblee [1966] and Minor and others [2009]) offshore for more than 7 km across the shelf, with a significant bend to the southwest (~230°). Although their seismic-reflection data did not image the Eagle Fault, they inferred its presence on the basis of offset fold trends. However, the high-resolution seismic-reflection data collected for our investigation (sheet 8) suggest that fold axes continue across their projection of the Eagle Fault; therefore, we infer that this fault either abruptly dies out offshore or continues its westerly strike north of the northern end of our seismic-reflection profiles (sheet 8).

The regional pattern of faults and earthquakes occurring between 1932 and 2010 that have inferred or measured magnitudes greater than 2.0 are shown on Map C on sheet 9. Although locations have been provided by the CalTech network since 1932, significantly greater precision began in 1969 with installation of a USGS seismographic network (see, for example, Lee and Vedder, 1973; Sylvester, 2001; Southern California Earthquake Data Center, 2010). Epicentral data indicate that seismicity in the eastern and central Santa Barbara Channel is characterized by earthquake swarms, relatively frequent minor earthquakes, and infrequent major earthquakes.

Three significant earthquakes affected the Santa Barbara Channel area in 1812, 1857, and 1925, prior to the time covered by the Southern California Earthquake Data Center (2010) catalog; however, locations in the northern Santa Barbara Channel have been reported (Sylvester and others, 1970) for both the 1925 event (M6.3) and the largest earthquake (~M5.5, 7/1/1941), which is shown on Map C (sheet 9). In addition, Sylvester and others (1970) documented a swarm of 62 earthquakes (M2.5–M5.2) that occurred between 6/26/1968 and 8/3/1968, which also were located 10 to 15 km south (offshore) of Santa Barbara. The largest event in the Offshore of Refugio Beach map area (~M4.4) occurred on 5/9/2004 about 7 km south of El Capitan Beach.

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 Refugio Beach map area (Maps A, B) and, to establish regional context, for a larger area (about 115 km of coast) that extends from the vicinity of Hueneme Canyon northwest to the Refugio Beach area (Maps D, E). 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 11) and two-way travel time (TWT). The thickness of the post-LGM unit (Maps B, E) was determined by applying a sound velocity of 1,600 m/sec to the TWT, resulting in thicknesses as great as 65 m. The thickness points were interpolated to a preliminary continuous surface, overlaid with zero-thickness bedrock outcrops (see sheet 10), and contoured (Wong and others, 2012). Data within Hueneme Canyon were excluded from the contouring because the seismic-reflection data are too sparse to adequately image the highly variable changes in sediment thickness that characterize the canyon (Maps D, E).

Several factors required manual editing of the preliminary sediment-thickness maps to make the final products. The Red Mountain Fault Zone, Pitas Point Fault, and Oak Ridge Fault disrupt the sediment sequence in the region (Maps D, E on sheet 9). The data points also are dense along tracklines (about 1 m apart) and sparse between tracklines (1–2 km apart), resulting in contouring artifacts. To incorporate the effect of the faults, to remove irregularities from interpolation, and to reflect other geologic information and complexity, the resulting interpolated contours were modified. Contour modifications and regridding were repeated several times to produce the final regional sediment-thickness map (Wong and others, 2012).

The depth-to-base data available from Seisworks were similarly processed and contoured; however, this preliminary dataset was set aside in favor of a surface determined by subtracting the modified thickness data from multibeam bathymetry collected separately (see sheet 1) and using 1,500 m/sec for TWT in the water column. The depth of this surface in the Hueneme Canyon to Refugio Beach area ranges from 12 to 190 m (Map D on sheet 9; see also, Wong and others, 2012).

Five different "domains" of sediment thickness, which are bounded either by faults or by Hueneme Canyon, are recognized on the regional maps (Maps D, E on sheet 9): (1) north of the south strand of the Red Mountain Fault Zone; (2) between the south strand of the Red Mountain Fault Zone and the Pitas Point Fault; (3) between the Pitas Point and Oak Ridge Faults; (4) between the Oak Ridge Fault and Hueneme Canyon; and (5) south of Hueneme Canyon. Table 7–1 shows the area of these five domains, along with estimates of their mean sediment thickness and total sediment volume. These data highlight the contrast among three general zones of sediment thickness: (1) the uplifted, sediment-poor Santa Barbara shelf (domain 1; mean sediment thickness of 3.5 m); (2) a transitional zone (domain 2; mean sediment thickness of 18.0 m); and (3) the subsiding, sediment-rich delta and shelf offshore of the Ventura and Santa Clara Rivers and Calleguas Creek (domains 3, 4, and 5; mean sediment thicknesses of 39.2, 38.9, and 28.3 m, respectively).

In the Offshore of Refugio Beach map area, thickness data (Map B on sheet 9) reveal that the post-LGM section has a mean thickness of just 2.7 m. Sediment is either notably lacking or it forms only a thin veneer over bedrock outcrops on the midshelf to outer shelf areas. Post-LGM sediment is thickest in three elongate, shore-parallel, coalescing, nearshore to inner shelf bars. These bars, which have positive seafloor relief and delta-mouth-bar morphology, are characterized by a relatively flat (about 0.7° to 1.4°) upper surface and a steeper (about 4.0°) seaward-dipping front. Local, steep, small coastal watersheds (Duvall and others, 2004) are the obvious predominant sediment source, and the width of the bar may, in part, reflect both sediment supply and the size of the adjacent watershed.

In the western part of the map area, the sediment-thickness map (Map B) reveals an elongate, shore-parallel bar that extends 800 to 1,000 m offshore and contains as much as 10 m of post-LGM sediment; the seismic-reflection profile in figure 1 on sheet 8 crosses the southern margin of this feature. This bar, which extends to the west for several kilometers (beyond the mouth of Gaviota Creek, 3 km west of the map area), and lies offshore of the mouths of steep, small (about 3 to 12 km^2) coastal watersheds (for example, Cañada del Molino; fig. 1–2). These local watersheds and the much larger Gaviota Creek (about 52 km^2; Warrick and Mertes, 2009) are the obvious predominant sediment source. Sediment thickness in this bar increases west of the map area to as much as 25 m offshore of Gaviota Creek.

Another bar is present in the central nearshore to inner shelf area (Map B) offshore of the mouths of Tajiquas Creek and Cañada del Refugio (fig. 1–2; both watersheds are about 12 km^2); its sediment thickness is as much as 7 m, and it similarly extends about 1,000 m offshore. The seismic-reflection profile in figure 6 on sheet 8 crosses the southern margin of this feature.

The third, easternmost bar is present in the inner-shelf area offshore of El Capitan Beach and the west and east forks of El Capitan Creek (each about 12.5 km^2; Duvall and others, 2004), and it hosts sediment as much as 12 m thick. The east-west-trending axis of sediment thickness associated with this bar lies about 800 to 1,000 m offshore (Map B), and the area where thicker sediment is present is noticeably broader than that which is associated with similar bars in the central and western parts of the map area. This increased breadth may partly reflect the relative subsidence associated with an east-west-trending syncline (fig. 8 on sheet 8; see also, sheet 10). Similar sediment thickening (at most, a few meters) in the axes of synclines also is apparent on a few other seismic-reflection profiles (for example, fig. 1 on sheet 8), consistent with active folding.

Table 7–1. Area, sediment-thickness, and sediment-volume data for California's State Waters in Santa Barbara Channel region, between Refugio Beach and Hueneme Canyon areas (domains 1–5), as well as in Offshore of Refugio Beach map area.

[Data from within Hueneme Canyon were not included in this analysis]

Regional sediment-thickness domains in Santa Barbara Channel region			
	Area (km^2)	**Mean sediment thickness (m)**	**Sediment volume (10^6 m^3)**
(1) Refugio Beach to south strand of Red Mountain Fault Zone	357.8	3.5	1,266
(2) South strand of Red Mountain Fault Zone to Pitas Point Fault	67.1	18.0	1,205
(3) Pitas Point Fault to Oak Ridge Fault	68.6	39.2	2,688
(4) Oak Ridge Fault to Hueneme Canyon	75.4	38.9	2,933
(5) South of Hueneme Canyon	53.9	28.3	1,527
Sediment thicknesses in Offshore of Refugio Beach map area			
Offshore of Refugio Beach map area	97.3	2.7	258

Chapter 8. Geologic and Geomorphic Map of the Offshore of Refugio Beach Map Area (Sheet 10)

By James E. Conrad, Andrew C. Ritchie, Samuel Y. Johnson, Gordon G. Seitz, and Carlos I. Gutierrez

Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Refugio Beach 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 1.33 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 onshore geology was compiled from Dibblee (1981a,b,c,d) and Minor and others (2009). Unit ages, which are largely from Minor and others (2009), reflect local stratigraphic relations.

The offshore part of the map area largely consists of a gently offshore-dipping (less than 1°) shelf underlain by sediments derived primarily from relatively small coastal watersheds that drain the Santa Ynez Mountains (fig. 1–2). Nearshore and shelf deposits are primarily sand (unit Qms) at water depths less than about 45 m. More fine-grained sediment (very fine sand, silt and clay) of unit Qmsf are mapped between depths of about 45 m and the shelf break, which occurs at about 90 m. The boundary between units Qms and Qmsf is based on observations and extrapolation from sediment sampling (see, for example, Reid and others, 2006) and camera ground-truth surveying (see sheet 6). It is important to note that the boundary between units Qms and Qmsf should be considered transitional and approximate and is expected to shift as a result of seasonal- to annual- to decadal-scale cycles in wave climate, sediment supply, and sediment transport. Fine-grained deposits that are similar to unit Qmsf also are mapped at water depths greater than 90 m, below the shelf break on the upper slope; however, here they are identified as a separate unit (unit Qmsl) because they are present at or below the distinct shelf-slope geomorphologic break.

Coarser grained deposits (units Qmsc, Qmscl, and Qsc), which are recognized on the basis of their high backscatter (sheet 3) and, in some cases, their moderate seafloor relief (sheets 1, 2), have three modes of occurrence. In the nearshore (10 to 30 m water depth), coarse-grained strata (sand and gravel) of unit Qmsc underlie laterally coalescing and discontinuous bars at the mouths of steep coastal watersheds. Coarser grained deposits of unit Qmscl form several distinct lobes at water depths of 25 to 70 m, about 600 to 3,000 m offshore; these lobes, which range in size from about 0.1 km^2 to about 1.9 km^2, are mapped on the basis of their high backscatter and subtle positive seafloor relief. These coarse-grained strata clearly were derived from fluvial point sources in the adjacent, steep Santa Ynez Mountains. An isolated patch of clast-supported cobbles (unit Qsc), which rests on bedrock southwest of Refugio State Beach at a water depth of about 76 m, also may have been deposited at the mouth of a coastal watershed when sea level was lower during the late Pleistocene.

Offshore bedrock exposures near El Capitan State Beach (fig. 1–2) are assigned to the Miocene Rincon Shale (Tr) and the Miocene Monterey Formation (Tm) on the basis of their proximity to coastal outcrops mapped by Dibblee (1981a,b). Much of the outer shelf (water depths of more than 70 m) is underlain by the undivided Tertiary bedrock unit (Tbu) or the undivided Tertiary and Quaternary bedrock unit (QTbu). On the basis of regional cross sections that are constrained by deep seismic-reflection data and borehole logs (Heck, 1998; Tennyson and Kropp, 1998; Forman and Redin, 2005; Redin, 2005), as well as on high-resolution seismic-reflection data (see sheet 8) coupled with proprietary oil-industry dartcore data (Ashley and others, 1977), these outer shelf outcrops consist of the late

Miocene and early Pliocene Sisquoc Formation and the overlying Pliocene and Pleistocene Pico Formation (both of which are mapped here as the undivided QTbu unit). These undivided rocks have been uplifted in a large, warped, south-dipping regional homocline that formed above the blind, north-dipping North Channel Fault. The fault tip is inferred to be about 2 km deep (that is, at two-way travel time of about 1.5 sec) about 6 to 7 km offshore, beneath the slope and just outside the limit of California's State Waters (see sheet 8).

This area has a long history of petroleum production (Barnum, 1998), and pockmarks (unit Qmp) caused by gas seeps are common features in the Offshore Refugio Beach map area. In 1962, Shell Oil Company discovered the Molino gas field (see fig. 1–2 in pamphlet) 4 km offshore, in the southwestern part of the map area. Natural gas production, achieved by onshore directional drilling of an offshore anticlinal trap, has been underway since the 1960s (Galloway, 1998).

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

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Marine sedimentary units			
Qmp	494,483	0.49	0.42
Qms	24,783,678	24.78	20.83
Qmsf	43,440,452	43.44	36.52
Qmsl	4,795,686	4.80	4.03
Qmsc	2,090,630	2.09	1.76
Qmscl	6,705,794	6.71	5.64
Qsc	26,299	0.03	0.02
Total, sedimentary units	82,337,022	82.34	69.21
Marine bedrock and (or) shallow bedrock units			
Qms/QTbu	8,915,979	8.92	7.49
Qms/Tbu	7,194,073	7.19	6.05
Qms/Tm	1,701,328	1.70	1.43
QTbu	8,775,763	8.78	7.38
Tbu	6,850,735	6.85	5.76
Tm	3,154,004	3.15	2.65
Tr	35,717	0.04	0.03
Total, bedrock units	36,627,599	36.63	30.79
Total, Offshore of Refugio Beach map area	118,964,621	118.96	100.00

DESCRIPTION OF MAP UNITS

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

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

Qms	**Marine nearshore and shelf deposits (late Holocene)**—Mostly sand; ripples common. Found on gently seaward-dipping (about 1°) surface that extends from nearshore to water depths of about 45 m
Qmsc	**Coarse-grained marine nearshore and shelf deposits (late Holocene)**—Ranges from coarse sand and gravel to boulders. Found in laterally coalescing to discontinuous nearshore (10 to 30 m water depth) bars at mouths of steep coastal watersheds. Recognized primarily on basis of high acoustic-backscatter intensity and moderate positive relief (see sheets 1–4)
Qmsf	**Fine-grained marine shelf deposits (late Holocene)**—Mostly clay, silt, and very fine sand; commonly bioturbated; found on gently seaward-dipping (about 0.7°) surface at depths greater than about 45 to 60 m and less than about 90 m
Qmp	**Marine pockmarks (late Holocene)**—Sand and mud, in circular to elliptical pockmarks. Pockmarks are solitary or grouped, and range in size from 50 to 150 m along their long axis; they typically are 20 cm to 40 cm deep and ringed with a convex rim as high as 150 cm
Qmsl	**Marine upper slope deposits (late Holocene)**—Predominantly clay, silt, and very fine sand; commonly bioturbated. Occurs below shelf break on seaward-dipping (about 5°) surface at water depths more than 90 m
Qmscl	**Marine shelf-sediment lobes (Holocene)**—Predominantly sand to boulders(?). Found as five distinct, irregularly shaped lobes, at water depths of 25 to 70 m, about 600 to 3,000 m offshore. Lobes, which range in size from about 0.1 km^2 to about 1.5 km^2, are mapped on basis of high backscatter intensity and subtle positive seafloor relief
Qsc	**Marine or nonmarine coarse-grained deposits (late Pleistocene?)**—Isolated outcrop of consolidated or semiconsolidated, flat-lying sedimentary strata, at least partly conglomeratic. Unconformably overlies folded marine sedimentary rocks of the undivided Pliocene and Miocene bedrock unit (Tbu). Deposit is inferred to be 2 to 3 m thick
QTbu	**Bedrock, undivided (Pleistocene to Miocene)**—Predominantly mudstone and siltstone; includes conglomeratic sandstone. Consists of Pliocene and Pleistocene Pico Formation and late Miocene and early Pliocene Sisquoc Formation. Stippled areas (composite unit Qms/QTbu) indicated where thin sheets of Qms overlie unit
Tbu	**Bedrock, undivided (Pliocene and Miocene)**—Mainly mudstone and siltstone. Possibly consists of the early Pliocene and Late Miocene Sisquoc Formation, the Miocene Monterey Formation, and the early Miocene Rincon Shale. Stippled areas (composite unit Qms/Tbu) indicate where thin sheets of Qms overlie unit
Tm	**Monterey Formation (Miocene)**—Predominantly well-bedded, siliceous and calcareous mudstone and shale. Stippled areas (composite unit Qms/Tm) indicate where thin sheets of Qms overlie unit
Tr	**Rincon Shale (early Miocene)**—Mostly mudstone, with subordinate dolomite, siliceous

shale, sandstone, and tuff

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units are compiled from from Dibblee (1981a,b,c,d) and Minor and others (2009); unit ages, which are derived from these sources, reflect local stratigraphic relations]

af	**Artificial fill (late Holocene)**—Engineered and (or) nonengineered
Qb	**Beach deposits (late Holocene)**—Unconsolidated, loose, fine- to coarse-grained sand; well sorted. Mapped in coastal band from shoreline to highest elevation of swash zone
Qyf	**Alluvium and colluvium, undivided (Holocene and late Pleistocene)**—Poorly consolidated silt, sand, and gravel deposits, in modern drainages and piedmont alluvial fans and floodplains
Qc	**Colluvium (Holocene and late Pleistocene)**—Poorly consolidated, poorly stratified, and poorly sorted deposits that mantle gentle to moderate slopes; formed by weathering and downslope movement of nearby bedrock
Qls	**Landslide deposits (Holocene to middle Pleistocene)**—Deposits of diverse slope-movement processes, ranging from poorly sorted, disrupted mixtures of rock fragments and soil to relatively intact bedrock slump blocks
Qomp	**Marine-terrace deposits (late Pleistocene)**—Basal, about 1 m thick, weakly to moderately well consolidated, variably stratified, fossiliferous gravel, sand, and silt; overlies nonmarine eolian, alluvial, and colluvial deposits; deposited as marine intertidal, beach, and estuarine deposits. Unit, which rests on elevated, marine wave-cut platforms, forms single terraces or flights of terraces that, in Santa Barbara coastal region, range in elevation from 10 to 130 m and in age from about 120 ka (oxygen-isotope stage 5) to 40 ka (substage 3) (Trecker and others, 1998; Gurrola and others, 2014)
Qoa	**Alluvial deposits (late and middle Pleistocene)**—Weakly consolidated, stratified silt, sand, gravel, conglomerate, breccia, and rare interbeds of clay, silt, and mudstone that form low, rounded, moderately well dissected terraces and piedmont alluvial fans. Found at elevations higher than the modern coastal-piedmont surface
Tsq	**Sisquoc Formation (early Pliocene and late Miocene)**—Marine, tan- to white-weathering, diatomaceous mudstone and shale, conglomerate, and subordinate dolomite. Unit distinguished by thick beds of conglomerate that contain angular clasts (commonly as much as 1 m across; some blocks as large as 10 m) derived from the Monterey Formation. Both top and base are erosional unconformities
Tm	**Monterey Formation, undivided (Miocene)**—Marine, predominantly well-bedded siliceous and calcareous mudstone and shale, with subordinate porcelanite and dolomite. Contains abundant microfossils. Unit deposited at water depths ranging from upper to lower bathyal (150–2,000 m; Isaacs, 2001). Maximum composite thickness in this region estimated to be about 830 m. In map area, the Monterey Formation is divided into the following subunit
Tml	**Lower calcareous unit (middle and early Miocene)**—Calcareous, siliceous, and phosphatic, white- to tan-weathering mudstone and shale, with subordinate dolomite, porcelanite, breccia, glauconitic sandstone, and tuff. In places, unit contains intraformational deformation (including breccia) that may have formed by gravitational slumping shortly after deposition
Tr	**Rincon Shale (early Miocene)**—Marine, primarily massive or thick-bedded, light-brown-weathering mudstone, with subordinate dolomite, siliceous shale, sandstone, and tuff.

	Mudstone is bioturbated and massive, is pervasively hackly fractured, and locally contains abundant microfossils. Single or multiple white-weathering tuff layers limited to upper 10 m
Tv	**Vaqueros Formation (late Oligocene)**—Shallow-marine, massive, and bioturbated, resistant, light-tan-weathering sandstone. Uppermost part consists of thinly interbedded sandstone, siltstone, and mudstone; base typically marked by 50- to 150-cm-thick, thinly bedded, calcareous conglomerate that contains abundant fossil-shell fragments
Tspu	**Sespe Formation, upper sandstone and mudstone unit (Oligocene)**—Interbedded sandstone, siltstone, and mudstone; weathers to various shades of maroon, buff, pale green, tan, and gray. Proportions of different sedimentary rock types vary both laterally and vertically throughout the section. Sandstones commonly are broadly lenticular, laminated, and thin to thick bedded
Ta	**Alegria Formation (Oligocene)**—Shallow-marine, arkosic sandstone and greenish-gray siltstone; locally fossiliferous; interfingers to east with the Sespe Formation (Dibblee, 1981a)
Tg	**Gaviota Formation (Oligocene and Eocene)**—Shallow-marine, thick-bedded arkosic sandstone and some gray siltstone; locally fossiliferous (Dibblee, 1981a)
Tgsl	**Lower unit (Oligocene and Eocene)**—Shallow-marine, gray, concretionary siltstone and claystone (Dibblee, 1981b)
Tg-sa	**Gaviota Formation and Sacate Formation, undivided (Oligocene and Eocene)**—Marine sandstone and siltstone; occurs in northwest corner of map area (Dibblee, 1981d)
Tcw	**Coldwater Sandstone (late? and middle Eocene)**—Shallow-marine, thin- to thick-bedded sandstone that weathers to distinctive pale shades of buff, yellow, tan, and brown, with subordinate interbeds and thin intervals of gray, olive-gray, and greenish-gray siltstone, shale, and mudstone. Sandstone beds are resistant and form hogbacks where steeply dipping. Upper part is locally conglomeratic and rich in fossil oyster shells
Ts	**Sacate Formation (Eocene)**—Marine, dark-gray micaceous siltstone and shale, with interbeds of hard arkosic sandstone (Dibblee, 1981d)
Tsa	**Sandstone subunit (Eocene)**—Marine, light-gray to tan arkosic sandstone (Dibblee, 1981d)
Tcd	**Cozy Dell Shale (Eocene)**—Marine, dark-gray argillaceous to silty micaceous shale with minor light-gray to tan arkosic sandstone
Tcds	**Sandstone interval (Eocene)**—Marine, light-gray to tan arkosic sandstone, with minor interbeds of gray micaceous shale
Tma	**Matilija Sandstone (Eocene)**—Marine, thick-bedded, arkosic sandstone
Tmas	**Sandstone and shale subunit (Eocene)**—Interbedded sandstone and shale
Tj	**Juncal Formation (Eocene)**—Marine shale
Tjs	**Sandstone unit (Eocene)**—Marine sandstone
Tan	**Anita Shale (Eocene and Paleocene)**—Marine, medium- to dark-gray micaceous shale, with thin sandstone layers (Dibblee, 1981c)
	Jalama Formation (Late Cretaceous)—Predominantly micaceous clay shale, with minor sandstone interbeds
Kjs	**Sandstone unit (Late Cretaceous)**—Marine sandstone (Dibblee, 1981d)
Kj	**Shale unit (Late Cretaceous)**—Marine shale (Dibblee, 1981d)

Chapter 9. Predicted Distribution of Benthic Macro-Invertebrates for the Offshore of Refugio Beach Map Area and the Santa Barbara Channel Region (Sheet 11)

By Lisa M. Krigsman, Mary M. Yoklavich, Nadine E. Golden, and Guy R. Cochrane

Modeling the distribution of ecologically and economically important species provides managers and conservation planners with information on a broad spatial scale that is useful to coastal management, ocean energy, marine protected areas, and marine spatial planning. Sheet 11 displays predictive models of occurrence for common benthic macro-invertebrate taxa and maps the probability of occurrence of these taxa in the Santa Barbara Channel region (Krigsman and others, 2012). These models are based on real-time biological observations of all macro-organisms made during ground-truth surveys (sheet 6) conducted in 2008 and 2009; the observations were made during a 10-second interval every minute along video transects, which were approximately 1 km in length (see sheet 6; see also, chapter 5 of this pamphlet). These transects produced a total of 923 observations from Refugio Beach (34.5° N., 120.1° W.) to Hueneme Canyon (34.1° N., 119.2° W.).

Five invertebrate taxa—cup corals, hydroids, short sea pens, tall sea pens, and brittle stars (which protrude out of the sediment)—were selected for modeling purposes because of their frequent occurrence in the Santa Barbara Channel; all are structure-forming components of valuable habitat for groundfish species (Krigsman and others, 2012). Presence-absence data for the selected invertebrates were fit to multiple generalized linear models using a combination of three covariates—geographic location, seafloor character (sheet 5), and shaded-relief bathymetry (sheet 2)—as well as relevant interaction terms. Geographic locations for the five observed invertebrates were derived from analysis of the video data from an area along the mainland coast of the Santa Barbara Channel; the Offshore of Carpinteria map area was excluded because of insufficient data. Three statistically different locations were identified on the basis of a community-structure analysis: (1) the Hueneme Canyon and Vicinity and Offshore of Ventura map areas; (2) the Offshore of Santa Barbara and Offshore of Coal Oil Point map areas; and (3) the Offshore of Refugio Beach map area. Best-fit models were selected for each invertebrate on the basis of Akaike's Information Criterion (AIC) (Akaike, 1974), a best-fit model being defined as the one that has the fewest parameters within two AIC points of the minimum score.

The seafloor in the Offshore of Refugio Beach map area has reefs made up of Class II (mixed habitat) and Class III (rugose rock) that are surrounded by large areas of Class I (unconsolidated sediment) (see sheet 5; see also, chapter 4 in this pamphlet). Cup corals (Map D on sheet 11), benthic cnidarians typically found on rocky habitats, have a very high (about 90 percent) probability of occurrence at depths deeper than 60 m where suitable habitat is present. The probability of observing cup corals also was very high on nearshore reefs. Hydroids (Map C on sheet 11), another benthic cnidarian found on rocky habitats, have a low probability of occurrence on nearshore reefs; however, as depth increases so does the probability of occurrence in areas of mixed sediment and rugose rock.

Sea pens, also members of the phylum Cnidaria, are divided into two groups—short and tall—on the basis of their size. Sea pens less than 60 cm in height are identified as short sea pens (*Stylatula* spp. and *Virgularia* spp.); those taller than 60 cm are identified as tall sea pens (*Halipteris* spp.) (Maps B and A, respectively, on sheet 11). Sea pens typically are associated with unconsolidated and mixed sediment because their rootlike base anchors them to the seafloor. Short sea pens have the highest probability of occurrence on unconsolidated sediment at depths between 30 and 60 m, whereas tall sea pens have the highest probability of occurrence at depths greater than 60 m.

Brittle stars (Map E on sheet 11) can occur in such high densities in the sediment that they create a thick carpet on the seafloor. Like sea pens, they typically are associated with unconsolidated and mixed sediment into which they burrow; however, they also are found in cracks and crevices within rugose rock. In the Offshore of Refugio Beach map area, brittle stars have a moderate probability of occurrence (about 70 percent) in unconsolidated sediment at depths between 30 and 60 m; however, at depths less than 30 m and also greater than 60 m, the probability of occurrence is low.

These predictive maps are based on data available from the California Seafloor Mapping Program (location, habitat type, and bathymetry). Other factors such as ocean currents (Cudaback and others, 2005), water temperature (Bingham and others, 1997), larval distribution (Grantham and others, 2003), and recruitment and mortality (Keough and Downes, 1982) also can significantly influence the distribution and abundance of these benthic macro-invertebrate taxa.

Acknowledgments

This publication was funded by the California Ocean Protection Council and the U.S. Geological Survey (USGS) Coastal and Marine Geology Program. Eric Grossman, Jon Warrick, and Scott Starratt (all USGS) provided constructive reviews. The publication benefitted from the significant effort Taryn Lindquist put into refining the design of the maps and pamphlet, and from editing by Sarah Nagorsen.

References Cited

Aikake, H., 1974, A new look at the statistical model identification: Institute of Electrical and Electronics Engineers Transactions on Automatic Control, v. 19, p. 716–723.

Anderson, T.J., Cochrane, G.R., Roberts, D.A., Chezar, H., and Hatcher, G., 2007, A rapid method to characterize seabed habitats and associated macro-organisms, *in* Todd, B.J., and Greene, H.G., eds., Mapping the seafloor for habitat characterization: Geological Association of Canada Special Paper 47, p. 71–79.

Ashley, R.J., Berry, R.W., and Fischer, P.J., 1977, Offshore geology and sediment distribution of the El Capitan-Gaviota continental shelf, northern Santa Barbara Channel, California: Journal of Sedimentary Petrology, v. 47, p. 199–208.

Barnard, P.L., Revell, D.L., Hoover, D., Warrick, J., Brocatus, J., Draut, A.E., Dartnell, P., Elias, E., Mustain, N., Hart, P.E., and Ryan, H.F., 2009, Coastal processes study of Santa Barbara and Ventura Counties, California: U.S. Geological Survey Open-File Report 2009–1029, 926 p., available at http://pubs.usgs.gov/of/2009/1029/.

Barnum, H.P., 1998, Redevelopment of the western portion of the Rincon offshore oil field, Ventura, California, *in* Kunitomi, D.S., Hopps, T.E., and Galloway, J.M., eds., Structure and petroleum geology, Santa Barbara Channel, California: American Association of Petroleum Geologists, Pacific Section, and Coast Geological Society, Miscellaneous Publication 46, p. 201–215.

Bingham, B.L., Bacigalupi, M., and Johnson, L.G., 1997, Temperature adaptations of embryos from intertidal and subtidal sand dollars (Dendraster excentricus, Eschscholtz): Northwest Science, v. 71(2), p. 108–114.

Briggs, J.C., 1974, Marine zoogeography: New York, McGraw-Hill, 480 p.

Caldwell, R.J., Taylor, L.A., Eakins, B.W., Carignan, K.S., Grothe, P.R., Lim, E., and Friday, D.Z., 2010, Digital elevation models of Santa Monica, California—Procedures, data sources and analysis: NOAA Technical Memorandum NESDIS NGDC-46, NOAA National Geophysical Data Center, available at http://www.ngdc.noaa.gov/dem/squareCellGrid/download/663.

California Department of Fish and Game, 2008, California Marine Life Protection Act master plan for marine protected areas—Revised draft: California Department of Fish and Game, available at http://www.dfg.ca.gov/mlpa/masterplan.asp.

Carignan, K.S., Taylor, L.A., Eakins, B.W., Warnken, R.R., Lim, E., and Medley, P.R., 2009, Digital elevation model of Santa Barbara, California—Procedures, data sources, and analysis: NOAA Technical Memorandum NESDIS NGDC-29, NOAA National Geophysical Data Center, available at http://www.ngdc.noaa.gov/dem/squareCellGrid/download/603.

Cochrane, G.R., 2008, Video-supervised classification of sonar data for mapping seafloor habitat, *in* Reynolds, J.R., and Greene, H.G., eds., Marine habitat mapping technology for Alaska: Fairbanks, University of Alaska, Alaska Sea Grant College Program, p. 185–194, available at http://doc.nprb.org/web/research/research%20pubs/615_habitat_mapping_workshop/Individual%20Chapters%20High-Res/Ch13%20Cochrane.pdf

Cochrane, G.R., Conrad, J.E., Reid, J.A., Fangman, S., and Golden, N., 2005, Nearshore benthic habitat GIS for the Channel Islands National Marine Sanctuary and southern California state fisheries reserves, vol. II: U.S. Geological Survey Open-File Report 2005–1170, available at http://pubs.usgs.gov/of/2005/1170/.

Cochrane, G.R., and Lafferty, K.D., 2002, Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California: Continental Shelf Research, v. 22, p. 683–690.

Cochrane, G.R., Nasby, N.M., Reid, J.A., Waltenberger, B., and Lee, K.M., 2003, Nearshore benthic habitat GIS for the Channel Islands National Marine Sanctuary and southern California state fisheries reserves, vol. I: U.S. Geological Survey Open-File Report 03–85, available at http://pubs.usgs.gov/of/2003/0085.

Cudaback, C.N., Washburn, L., and Dever, E., 2005, Subtidal inner-shelf circulation near Point Conception, California: Journal of Geophysical Research, v. 110, C10007, doi:10.1029/2004JC002608.

Dibblee, T.W., Jr., 1966, Geology of the central Santa Ynez Mountains, Santa Barbara County: California Division of Mines and Geology Bulletin 186, 99 p.

Dibblee, T.W., Jr., 1981a, Geologic map of the Tajiguas quadrangle, California: U.S. Geological Survey Open-File Report 81–371, scale 1:24,000.

Dibblee, T.W., Jr., 1981b, Geologic map of the Gaviota quadrangle, California: U.S. Geological Survey Open-File Report 81–374, scale 1:24,000.

Dibblee, T.W., Jr., 1981c, Geologic map of the Santa Ynez quadrangle, California: U.S. Geological Survey Open-File Report 81–373, scale 1:24,000.

Dibblee, T.W., Jr., 1981d, Geologic map of the Solvang quadrangle, California: U.S. Geological Survey Open-File Report 81–372, scale 1:24,000.

Draut, A.E., Hart, P.E., Lorenson, T.D., Ryan, H.F., Wong, F.L., Sliter, R.W., and Conrad, J.E., 2009, Late Pleistocene to Holocene sedimentation and hydrocarbon seeps on the continental shelf of a steep, tectonically active margin, southern California, USA: Marine Geophysical Research, p. 193–206, doi:10.1007/s11001-009-9076-y.

Duvall, A., Kirby, E., and Burbank, D., 2004, Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California: Journal of Geophysical Research, v. 109, 18 p., F03002, doi:10.1029/2003JF000086,2004.

Fader, G.B.J., 1997, Effects of shallow gas on seismic-reflection profiles, *in* Davies, T.A., Bell, T., Cooper, A.K., Josenhaus, H., Polyak, L., Solheim, A., Stoker, M.S., and Stravers, J.A., eds., Glaciated continental margins—An atlas of acoustic images: London, Chapman & Hall, p. 29–30.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record—Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Science, v. 342, p. 637–642.

Fisher, M.A., Normark, W.R., Greene, H.G., Lee, H.J., and Sliter, R.W., 2005, Geology and tsunamigenic potential of submarine landslides in Santa Barbara Channel, southern California: Marine Geology, v. 224, p. 1–22.

Fisher, M.A., Sorlien, C.C., and Sliter, R.W., 2009, Potential earthquake faults offshore southern California from the eastern Santa Barbara channel to Dana Point, *in* Lee, H.J., and Normark, W.R., eds., Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 271–290.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., and Chappell, J., 1998, Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites: Earth and Planetary Science Letters, v. 163, p. 327–342, doi:10.1016/S0012-821X(98)00198-8.

Forman, J., and Redin, T., 2005, Santa Barbara Channel structure and correlation sections—Correlation Section no. 37, Arroyo Hondo, Gaviota quadrangle, Santa Ynez Mountains to northwest Santa Rosa Island: American Association of Petroleum Geologists, Pacific Section, Publication CS 37, 1 sheet.

Galloway, J.M., 1998, Chronology of petroleum exploration and development in the Santa Barbara channel area, offshore southern California, *in* Kunitomi, D.S., Hopps, T.E., and Galloway, J.M., eds., Structure and petroleum geology, Santa Barbara Channel, California: American Association of Petroleum Geologists, Pacific Section, and Coast Geological Society, Miscellaneous Publication 46, p. 1–12, 1 sheet.

Gotshall, D.W., 2005, Guide to marine invertebrates—Alaska to Baja (2d ed.): Monterey, Calif., Sea Challengers, 117 p.

Grantham, B.A., Eckert, G.L., and Shanks, A.L., 2003, Dispersal potential of marine invertebrates in diverse habitats: Ecological Applications, v. 13(1), supplement p. S108–S116.

Greene, H.G., Bizzarro, J.J., O'Connell, V.M., and Brylinsky, C.K., 2007, Construction of digital potential marine benthic habitat maps using a coded classification scheme and its application, *in* Todd, B.J., and Greene, H.G., eds., Mapping the seafloor for habitat characterization: Geological Association of Canada Special Paper 47, p. 141–155.

Greene, H.G., Bizzarro, J.J., Tilden, J.E., Lopez, H.L., and Erdey, M.D., 2005, The benefits and pitfalls of geographic information systems in marine benthic habitat mapping, *in* Wright, D.J., and Scholz, A.J., eds., Place matters: Portland, Oregon State University Press, p. 34–46.

Greene, H.G., Murai, L.Y., Watts, P., Maher, N.A., Fisher, M.A., and Eichhubl, P., 2006, Submarine landslides in the Santa Barbara channel as potential tsunami sources: Natural Hazards and Earth System Sciences, v. 6, p. 63–88.

Greene, H.G., Yoklavich, M.M., Starr, R.M., O'Connell, V.M., Wakefield, W.W., Sullivan, D.E., McRea, J.E., and Cailliet, G.M., 1999, A classification scheme for deep seafloor habitats: Oceanologica Acta, v. 22, p. 663–678.

Griggs, G., Patsch, K., and Savoy, L., 2005, Living with the changing California coast: Berkeley, University of California Press, 540 p.

Gurrola, L.D., Keller, E.A., Chen, J.H., Owen, L.A., and Spencer, J.Q., 2014, Tectonic geomorphology of marine terraces—Santa Barbara fold belt, California: Geological Society of America Bulletin, v. 126, p. 219–233.

Hapke, C.J., and Reid, D.R., 2007, National assessment of shoreline change, part 4—Historical coastal cliff retreat along the California Coast: U.S. Geological Survey Open-File Report 2007–1133, 51 p., available at http://pubs.usgs.gov/of/2007/1133/.

Hapke, C.J., Reid, D., Richmond, B.B., Ruggiero, P., and List, J., 2006, National assessment of shoreline change, part 3—Historical shoreline change and associated coastal land loss along sandy shorelines of the California coast: U.S. Geological Survey Open-File Report 2006–1219, 72 p., available at http://pubs.usgs.gov/of/2006/1219/.

Heck, R.G., 1998, Santa Barbara Channel regional formline map, top Monterey Formation, *in* Kunitomi, D.S., Hopps, T.E., and Galloway, J.M., eds., Structure and petroleum geology, Santa Barbara Channel, California: American Association of Petroleum Geologists, Pacific Section, and Coast Geological Society, Miscellaneous Publication 46, 1 plate.

Hornafius, J.S., Luyendyk, B.P., Terres, R.R., and Kamerling, M.J., 1986, Timing and extent of Neogene rotation in the western Transverse Ranges, California: Geological Society of America Bulletin, v. 97, p. 1,476–1,487.

Hovland, M., and Judd, A.G., 1988, Seabed pockmark and seepages: London, Graham and Trotman, Inc., 293 p.

Isaacs, C.M., 2001, Depositional framework of the Monterey Formation, California, *in* Isaacs, C.M., and Rullkötter, J., eds., The Monterey Formation—From rocks to molecules: New York, Columbia University Press, p. 1–30.

Jennings, C.W., and Bryant, W.A., 2010, Fault activity map of California: California Geological Survey Geologic Data Map no. 6, scale 1:750,000.

Keough, M.J., and Downes, B.J., 1982, Recruitment of marine invertebrates—The role of active larval choices and early mortality: Oecologia, v. 54, 348–352.

Kern, J.P., 1977. Origin and history of upper Pleistocene marine terraces, San Diego, California: Geological Society of America Bulletin, v. 88, p. 1,553–1,566.

Krigsman, L.M., Yoklavich, M.M., Dick, E.J., and Cochrane, G.R., 2012, Models and maps—Predicting the distribution of corals and other benthic macro-invertebrates in shelf habitats: Ecosphere, v. 3(1), article 3, 16 p., doi:http://dx.doi.org/10.1890/ES11-00295.1.

Kunitomi, D.S., Hopps, T.E., and Galloway, J.M., eds., 1998, Structure and petroleum geology, Santa Barbara Channel, California: American Association of Petroleum Geologists, Pacific Section, and Coast Geological Society, Miscellaneous Publication 46, 328 p.

Kvitek, R., Bretz, C., Cochrane, G.R., and Greene, H.G., 2006, Final report, Statewide Marine Mapping Planning Workshop, December 12–13, 2005, Seaside, Calif.: California State University, Monterey Bay, 108 p., available at http://euclase.csumb.edu/DATA_DOWNLOAD/StrategicMapgWrkshp05/MappingWorkshop12_12-13/Final_Report/CA%20Habitat%20Mapping%20Rpt.pdf.

Kvitek, R.G., Phillips, E.L., and Dartnell, P., 2012, Colored shaded-relief bathymetry, Hueneme Canyon and Vicinity, California, *sheet 1 in* Johnson, S.Y., Dartnell, P., Cochrane, G.R., Golden, N.E., Phillips, E.L., Ritchie, A.C., Kvitek, R.G., Greene, H.G., Krigsman, L.M., Endris, C.A., Clahan, K.B., Sliter, R.W., Wong, F.L., Yoklavich, M.M., and Normark, W.R. (S.Y. Johnson, ed.), California State Waters Map Series—Hueneme Canyon and Vicinity, California: U.S. Geological Survey Scientific Investigations Map 3225, pamphlet 41 p., 12 sheets, available at http://pubs.usgs.gov/sim/3225/.

Lambeck, K., and Chappell, J., 2001, Sea level change through the last glacial cycle: Science, v. 292, p. 679–686, doi:10.1126/science.1059549.

Larson, K.M., and Webb, F.H., 1992, Deformation in the Santa Barbara Channel from GPS measurements 1987–1991: Geophysical News Letters, v. 19, p. 1,491–1,494.

Lee, H.J., Greene, H.G., Edwards, B.D., Fisher, M.A., and Normark, W.R., 2009, Submarine landslides in the southern California borderland, *in* Lee, H.J., and Normark, W.R., eds., Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 251–269.

Lee, H.J., and Normark, W.R., eds., 2009, Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, 481 p.

Lee, W.H.K., and Vedder, J.G., 1973, Recent earthquake activity in the Santa Barbara Channel region: Bulletin of the Seismological Society of America, v. 63, p. 1,757–1,773.

Luyendyk, B.P., Kamerling, M.J., and Terres, R.R., 1980, Geometric model for Neogene crustal rotations in southern California: Geological Society of America Bulletin, v. 91, p. 211–217.

Madden, C.J., Goodin, K.L., Allee, R., Finkbeiner, M., and Bamford, D.E., 2008, Draft Coastal and Marine Ecological Classification Standard: National Oceanic and Atmospheric Administration (NOAA) and NatureServe, v. III, 77 p.

Metcalf, J.G., 1994, Morphology, chronology, and deformation of Pleistocene marine terraces, southwestern Santa Barbara County, Santa Barbara, California: Santa Barbara, University of California, M.S. thesis, 168 p.

Minor, S.A., Kellogg, K.S., Stanley, R.G., Gurrola, L.D., Keller, E.A., and Brandt, T.R., 2009, Geologic map of the Santa Barbara coastal plain area, Santa Barbara County, California: U.S. Geological Survey Scientific Investigations Map 3001, scale 1:25,000, 1 sheet, pamphlet 38 p., available at http://pubs.usgs.gov/sim/3001/.

Muhs, D.R., Rockwell, T.K., and Kennedy, G.L., 1992, Late Quaternary uplift rates of marine terraces on the Pacific Coast of North America, southern Oregon to Baja California Sur: Quaternary International, v. 15/16, p. 121–133.

National Oceanic and Atmospheric Administration, 2011, Coastal ifSAR: Digital Coast, NOAA Coastal Services Center database, accessed April 5, 2011, at http://www.csc.noaa.gov/digitalcoast/.

Nicholson, C., Sorlien, C., Atwater, T., Crowell, J.C., and Luyendyk, B.P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system: Geology, v. 22, p. 491–495.

Normark, W.R., Piper, D.J.W., Romans, B.W., Covault, J.A., Dartnell, P., and Sliter, R.W., 2009, Submarine canyon and fan systems of the California Continental Borderland, *in* Lee, H.J., and

Normark, W.R., eds., Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 141–168.

O'Reilly, W.C., and Guza, R.T., 1993, A comparison of spectral wave models in the Southern California Bight: Coastal Engineering, v. 19, p. 263–282, doi:10.1016/0378-3839(93)90032-4.

Peltier, W.R., 2005, On the hemispheric origins of meltwater pulse 1a: Quaternary Science Reviews, v. 24, p. 1,655-1,671.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, p. 3,322–3,337.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p., available at http://pubs.usgs.gov/of/2008/1128/.

Redin, T., 2005, Santa Barbara Channel structure and correlation sections—Correlation Section no. 36, N–S structure and correlation section, western Santa Ynez Mountains across the Santa Barbara channel to Santa Rosa Island: American Association of Petroleum Geologists, Pacific Section, Publication CS 36, 1 sheet.

Reid, J.A., Reid, J.M., Jenkins, C.J., Zimmerman, M., Williams, S.J., and Field, M.E., 2006, usSEABED—Pacific Coast (California, Oregon, Washington) offshore surficial-sediment data release: U.S. Geological Survey Data Series 182, available at http://pubs.usgs.gov/ds/2006/182/.

Slater, R.A., Gorsline, D.S., Kolpack, R.L., and Shiller, G.I., 2002, Post-glacial sediments of the California shelf from Cape San Martin to the US-Mexico border: Quaternary International, v. 92, p. 45–61.

Sliter, R.W., Triezenberg, P.J., Hart, P.E., Draut, A.E., Normark, W.R., and Conrad, J.E., 2008, High-resolution chirp and mini-sparker seismic reflection data from the southern California continental shelf—Gaviota to Mugu Canyon: U.S. Geological Survey Open-File Report 2008–1246, available at http://pubs.usgs.gov/of/2008/1246/.

Sommerfield, C.R., Lee, H.J., and Normark, W.R., 2009, Postglacial sedimentary record of the southern California continental shelf and slope, Point Conception to Dana Point, *in* Lee, H.J., and Normark, W.R., eds., Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 89–116.

Southern California Earthquake Data Center, 2010, Southern California Earthquake Catalog: Southern California Earthquake Data Center database, accessed April 5, 2011, at http://www.data.scec.org/eq-catalogs/index.html.

Stanford, J.D., Hemingway, R., Rohling, E.J., Challenor, P.G., Medina-Elizalde, M., and Lester, A.J., 2011, Sea-level probability for the last deglaciation—A statistical analysis of far-field records: Global and Planetary Change, v. 79, p. 193–203, doi:10.1016/j.gloplacha.2010.11.002.

Sylvester, A.G., 2001, Catalog of Santa Barbara earthquakes—1800 to 1960: University of California, Santa Barbara, database, accessed April 5, 2011, at http://projects.crustal.ucsb.edu/sb_eqs/SBEQCatlog/SBEQCATINTRO.html.

Sylvester, A.G., Smith, S.S., and Scholz, C.H., 1970, Earthquake swarm in the Santa Barbara Channel, California, 1968: Bulletin of the Seismological Society of America, v. 60, p. 1,047–1,060.

Tennyson, M.E., and Kropp, A.P., 1998, Regional cross section across Santa Barbara channel from northwestern Santa Rosa Island to Canada de Molino, *in* Kunitomi, D.S., Hopps, T.E., and Galloway, J.M., eds., Structure and petroleum geology, Santa Barbara Channel, California: American Association of Petroleum Geologists, Pacific Section, and Coast Geological Society, Miscellaneous Publication 46, 1 plate.

Tissot, B.N., Yoklavich, M.M., Love, M.S., York, K., and Amend, M., 2006, Benthic invertebrates that form habitat on deep banks off southern California, with special reference to deep sea coral: Fishery Bulletin, v. 104, p. 167–181.

Trecker, M.A., Gurrola, L.D., and Keller, E.A., 1998, Oxygen-isotope correlation of marine terraces and uplift of the Mesa Hills, Santa Barbara, California, USA, *in* Stewart, I.S., and Vita-Finzi, eds., Coastal Tectonics: Geological Society, London, Special Publications, v. 146, p. 57–69.

U.S. Geological Survey, 2009, National Archive of Marine Seismic Surveys: U.S. Geological Survey database, accessed April 5, 2011, at http://walrus.wr.usgs.gov/NAMSS/.

Warrick, J.A., and Farnsworth, K.L., 2009, Sources of sediment to the coastal waters of the Southern California Bight, *in* Lee, H.J., and Normark, W.R., eds., Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 39–52.

Warrick, J.A., and Mertes, L.A.K., 2009, Sediment yield from the tectonically active semiarid Western Transverse Ranges of California: Geological Society of America Bulletin, v. 121, p. 1,054–1,070.

Weber, K.M., List, J.H., and Morgan, K.L., 2005, An operational Mean High Water datum for determination of shoreline position from topographic lidar data: U.S. Geological Survey Open-File Report 2005–1027, available at *http://pubs.usgs.gov/of/2005/1027/.*

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377–392.

Wong, F.L., Phillips, E.L., Johnson, S.Y, and Sliter, R.W., 2012, Modeling of depth to base of Last Glacial Maximum and seafloor sediment thickness for the California State Waters Map Series, eastern Santa Barbara Channel, California: U.S. Geological Survey Open-File Report 2012–1161, 16 p., available at http://pubs.usgs.gov/of/2012/1161/.

Wright, J.D., 2000, Global climate change in marine stable isotope records, *in* Noller, J.S., Sowers, J.M., and Lettis, W.R., eds., Quaternary geochronology—Methods and applications: American Geophysical Union, p. 427–433.

Xu, J.P., and Noble, M.A., 2009, Variability of the southern California wave climate and implications for sediment transport, *in* Lee, H.J., and Normark, W.R., eds., Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 171–192.