California State Waters Map Series—Offshore of Santa Barbara, California

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

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

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(Samuel Y. Johnson[1] and Susan A. Cochran,[1] editors)

Preface

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

is published as a PDF file. Geographic information system (GIS) files that contain both ESRI[6] ArcGIS raster grids (for example, bathymetry, seafloor character) and geotiffs (for example, shaded relief) are also included for each publication. For those who do not own the full suite of ESRI GIS and mapping software, the data can be read using ESRI ArcReader, a free viewer that is available at http://www.esri.com/software/arcgis/arcreader/index.html (last accessed March 5, 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.

[6] Environmental Systems Research Institute, Inc.

Chapter 1. Introduction

By Samuel Y. Johnson

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

The city of Santa Barbara (population, about 92,000) is the main coastal population center, part of a contiguous urban area (population, about 220,000) that extends from Carpinteria to Goleta (fig. 1–1). This urban area was developed south of the east-west-trending Santa Ynez Mountains on coalescing alluvial surfaces, uplifted marine terraces, and low (elevations as high as about 130 m), east-west-trending hills underlain by folded and faulted Miocene bedrock (Minor and others, 2009). The crest of the Santa Ynez Mountains, about 1,100 m high, lies about 11 km north of the shoreline.

The Santa Barbara coastal zone is actively utilized. Development of the Santa Barbara Harbor began in 1928 (Griggs and others, 2005). The initial breakwater trapped sand, leading to shoaling within and west of the harbor, as well as coastal erosion east of the harbor. Annual harbor dredging, which began in 1959, averages about 400,000 tons/yr, mitigating at least some of the downcoast erosion problem. Beach recreation is popular in the Offshore of Santa Barbara map area, at sites such as Arroyo Burro Beach Park and Leadbetter Beach, west of the harbor, and East Beach and “Butterfly Beach” east of the harbor; “Hammonds Reef” offshore of Montecito is a well-known surfing locale (fig. 1–2).

The Offshore of Santa Barbara map area lies in the 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 Santa Barbara map area, these coastal watersheds include (from east to west) San Ysidro Creek, Oak Creek, Montecito Creek, Sycamore Creek, Mission Creek, Arroyo Burro, and Atascadero Creek (fig. 1–2). The much larger Ventura and Santa Clara Rivers, the mouths of which are 40 to 50 km southeast of Santa Barbara, yield an estimated 3.4 million tons of sediment annually (Warrick and Farnsworth, 2009), the coarser sediment load generally moving southeast down the coast and the finer sediment load moving both upcoast and offshore (Drake, 1972; Warrick and Farnsworth, 2009). 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 El Niño phases of the El Niño–Southern Oscillation (ENSO) climatic pattern (Warrick and Farnsworth, 2009).

Narrow beaches and cliffs characterize much of the shoreline in the Offshore of Santa Barbara map area. Continuing coastal erosion problems in the area are associated with both development and natural processes (summarized in Griggs and others, 2005; Barnard and others, 2009); cliff erosion is occurring at rates of about 0.1 to 1 m/yr over the period between 1933–1934 and 1998, the largest amount (63 m) occurring at Arroyo Burro in the western part of the map area (Hapke and Reid, 2007).

Hapke and others (2006, their fig. 35) suggested that beaches in this area have a mixed erosional to accretionary history over the long term (between the mid-1800s and 1998) but an erosional trend over the short term (from the mid-1970s to 1998).

The Offshore of Santa Barbara map area consists of relatively flat and shallow continental shelf. The shelf dips gently seaward (about 0.4° to 0.8°), so that water depths at the 3-nautical-mile (5.6-km) limit of California's State Waters range from about 45 m (at the eastern map margin) to about 75 m (at the western map margin). The shelf break is about 7 to 12 km south of the shoreline (outside the map area), at water depths of about 90 to 100 m. 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 the south and southwest 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 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 variable amounts (0 to 14 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, Dahlen, 1992; Slater and others, 2002; Draut and others, 2009).

The Offshore of Santa Barbara map area lies within the Shelf (continental shelf) megahabitat of Greene and others (2007). Habitat types range from soft, unconsolidated sediment to hard sedimentary bedrock. Some bedrock outcrops are covered by a thin ephemeral sediment layer, producing a mixed hard-soft habitat type. This heterogeneous seafloor provides promising habitat for rockfish (*Sebastes* spp.), groundfish, crabs, shrimp, and other marine benthic organisms.

The Offshore of Santa Barbara 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[7] (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 shortening (see, for example, Larson and Webb, 1992). In the map area, this shortening is accommodated by west- to northwest-striking, north-dipping (for example, Red Mountain Fault) and south-dipping (for example, Rincon Creek Fault) blind structures, as well as by fault-related folding. Cross sections by Redin (2005) and Redin and others (2005) suggest that these contractional faults merge at depth (about 5 to 6 km deep), and they further suggest that these structures have a component of left-lateral slip.

Uplift rates that are based on studies of onland marine terraces provide further evidence of significant shortening. Trecker and others (1998) and Keller and Gurrola (2000) mapped flights of four to five uplifted marine terraces along much of this coast, which range in elevation from 36 to 143 m; these terraces are inferred to have formed during the sea-level highstands of marine oxygen-isotopic stages 7 (about 160,000 to 250,000 years ago), 5 (about 80,000 to 120,000 years ago), and 3 (about 35,000 to 70,000 years ago) (Chappell, 1983; Chappell and Shackleton, 1986). The presence of emergent stage 3 terraces, which are uncommon along the California coast, requires rapid uplift: estimated rates of uplift (based on marine terrace elevations and geochronology) range from 0.7 ± 0.1 mm/yr at Summerland, a few kilometers east of the map area (fig. 1–1), to 2.2 ± 0.3 mm/yr at More Mesa, in the western part of the map area (fig. 1–2).

Fault-related structures have controlled the origins of offshore oil fields in the map area (Kunitomi and others, 1998; Heck, 1998). The offshore Summerland oil field is in the uplifted block

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

between the Red Mountain and Rincon Creek Faults. To the south and east of the map area, the Rincon Anticline hosts the offshore Rincon, Carpinteria, and Dos Cuadras oil fields. Similarly, to the west of the map area, the Coal Oil Point and South Ellwood oil fields lie along anticlines. No hydrocarbon development or production has occurred in the map area's state waters, which are part of the protected California Coastal Sanctuary, established in 1955, that extends from Summerland on the east to Goleta on the west (fig. 1–1). However, an oil-well drilling accident in 1969 in the newly discovered Dos Cuadras oil field, in federal waters about 10 km due south of Santa Barbara, led to the Santa Barbara oil spill, a leak of between 7,000 and 70,000 barrels (Galloway, 1998). Public reaction to the spill is credited for a host of new environmental laws and regulations (Clarke and Hemphill, 2002).

Publication Summary

This publication about the Offshore of Santa Barbara 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 four different sonar surveys to generate comprehensive high-resolution bathymetry and acoustic-backscatter coverage of the map area. These data reveal a range of physiographic features (highlighted in the perspective views on sheet 4) such as the flat, sediment-covered Santa Barbara shelf interspersed with tectonically controlled bedrock uplifts, coarse-grained deltas and sediment lobes associated with coastal watersheds, and patches of irregular seafloor related to hydrocarbon seeps. 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, rugosity (ruggedness), and backscatter intensity and which is further informed by the ground-truth-survey imagery. Sheet 7 is a map of "potential habitats," which are delineated on the basis of substrate type, geomorphology, seafloor process, or other attributes that may provide a habitat for a specific species or assemblage of organisms. Sheet 8 compiles representative seismic-reflection profiles from the map area, providing information on the subsurface stratigraphy and structure of the map area. Sheet 9 shows the distribution and thickness of young sediment (deposited over the last about 21,000 years, during the most recent sea-level rise) in both the map area and the larger Santa Barbara Channel region (offshore from Refugio Beach to Hueneme Canyon), interpreted on the basis of the seismic-reflection data. Sheet 10 is a geologic map that merges onshore geologic mapping (compiled from existing maps by the California Geological Survey) and new offshore geologic mapping that is based on the 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 Santa Barbara 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 the development of regional sediment-management plans. In addition, siting of any new offshore infrastructure (for example, pipelines, cables, or renewable-energy facilities) will depend on high-resolution mapping. Finally, this mapping will both stimulate and enable new scientific research and also raise public awareness of, and education about, coastal environments and issues.

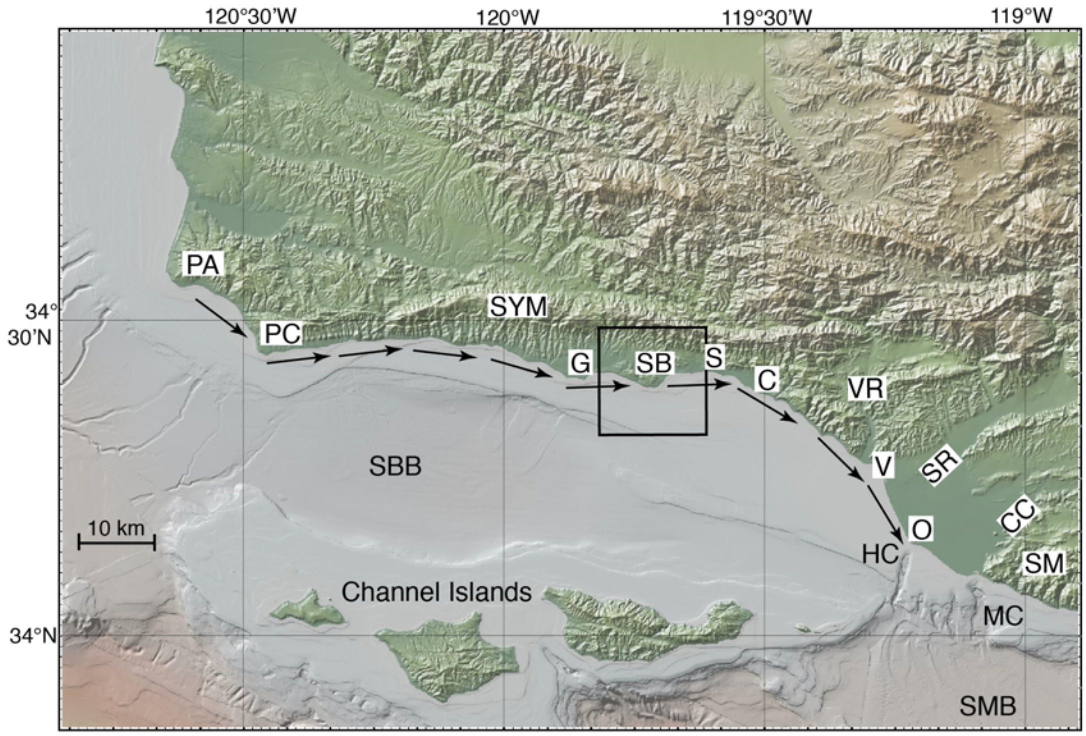

Figure 1–1. Physiography of Santa Barbara Channel region. Box shows Offshore of Santa Barbara map area. Arrows show direction of sediment transport in Santa Barbara littoral cell, which extends from Point Arguello (PA) to Hueneme Canyon (HC) and Mugu Canyon (MC). Other abbreviations: C, Carpinteria;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

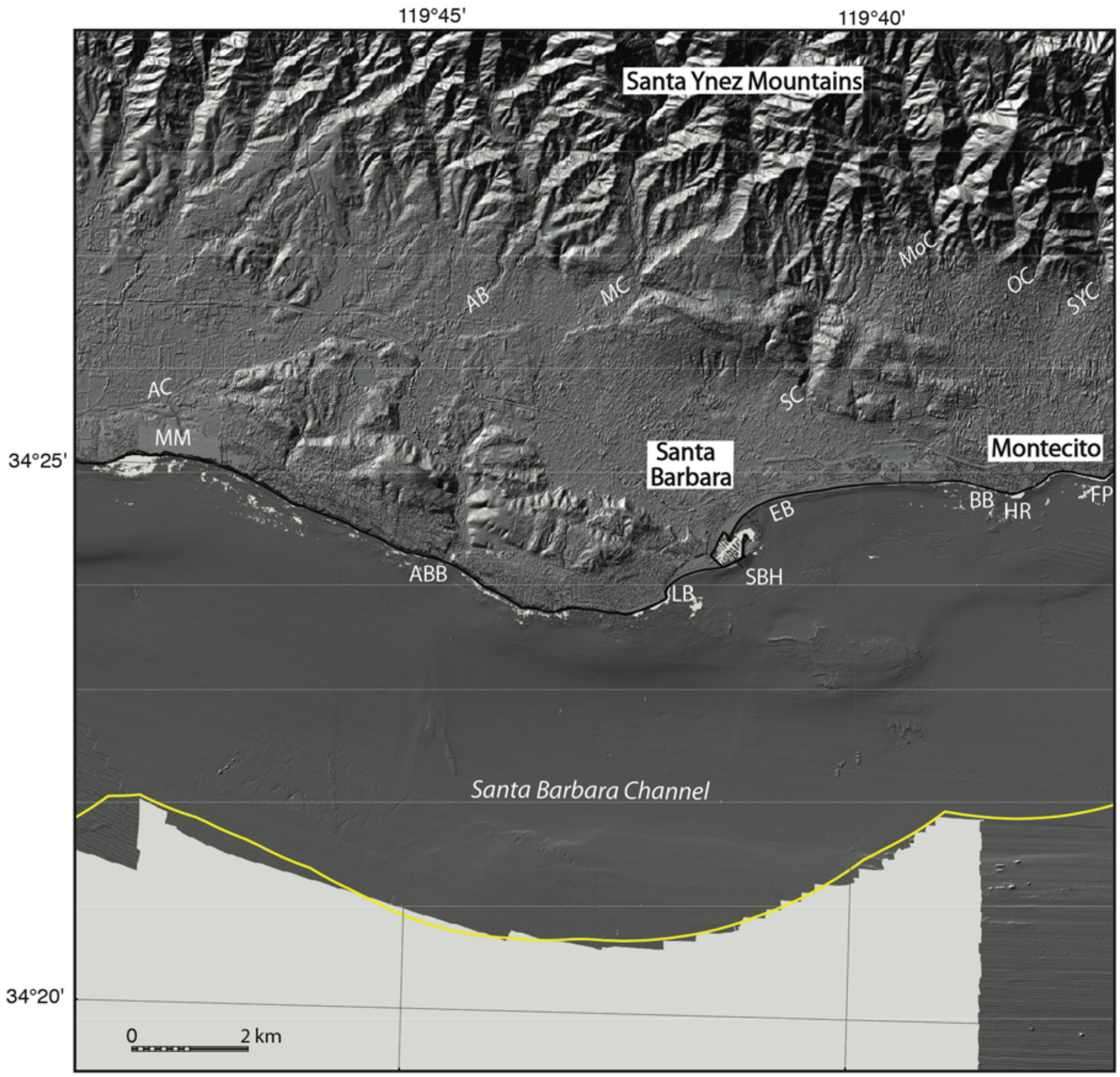

Figure 1–2. Coastal geography of Offshore of Santa Barbara map area. Abbreviations: AB, Arroyo Burro; ABB, Arroyo Burro Beach Park; AC, Atascadero Creek; BB, "Butterfly Beach;" EB, East Beach; FP, Fernald Point; HR, "Hammonds Reef;" LB, Leadbetter Beach; MC, Mission Creek; MM, More Mesa; MoC, Montecito Creek; OC, Oak Creek; SBH, Santa Barbara Harbor; SC, Sycamore Creek; SYC, San Ysidro Creek. Yellow line is 3-nautical-mile limit of California's State Waters.

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

By Peter Dartnell and Rikk Kvitek

The colored shaded-relief bathymetry (sheet 1), the shaded-relief bathymetry (sheet 2), and the acoustic-backscatter (sheet 3) maps of the Offshore of Santa Barbara map area in southern California were generated from bathymetry and backscatter data collected by California State University, Monterey Bay (CSUMB), 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). Most of the offshore area was mapped by CSUMB in the summer of 2007, using a 244-kHz Reson 8101 multibeam echosounder. Smaller areas in the far-east nearshore, as well as further offshore to the west and in the southeast outer shelf area, were mapped by the USGS in 2005 and 2006, using a combination of 468-kHz (2005) and 117-kHz (2006) SEA (AP) Ltd. SWATHplus-M phase-differencing sidescan sonars. 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 CSUMB mapping mission, an Applanix position and motion compensation system (POS/MV) was used to accurately position the vessel during data collection, and it also accounted for vessel motion such as heave, pitch, and roll (position accuracy, ±2 m; pitch, roll, and heading accuracy, ±0.02°; heave accuracy, ±5%, or 5 cm). NavCom 2050 GPS receiver (CNAV) data were used to account for tidal-cycle fluctuations, and sound-velocity profiles were collected with an Applied Microsystems (AM) SVPlus sound velocimeter. Soundings were corrected for vessel motion using the Applanix POS/MV data, for variations in water-column sound velocity using the AM SVPlus data, and for variations in water height (tides) using vertical-position data from the CNAV receiver. Backscatter data were postprocessed using CARIS7.0/Geocoder software. Geobars were created for each survey line using the beam-averaging engine. Intensities were radiometrically corrected (including despeckling and angle-varying gain adjustments), and the position of each acoustic sample was geometrically corrected for slant range on a line-by-line basis. The contrast and brightness of some geobars were adjusted to better match the surrounding geobars. Individual geobars were mosaicked together at 2-m resolution using the auto-seam method. The mosaics were then exported from CARIS as georeferenced TIFF images, imported into a geographic information system (GIS), and converted to GRIDs.

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

During the Fugro Pelagos 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, even though the surveys were conducted at different times using different mapping equipment. For example, a mean difference of 0.12 m (0.12 standard deviation) exists between the 2007 CSUMB multibeam-echosounder data and the overlapping 2009 USACE bathymetric-lidar data, even though the overlap is in the energetic nearshore region that is highly susceptible to natural change. A mean difference of 0.32 m (0.14 standard deviation) also is present between the 2006 USGS nearshore SWATHplus data and the overlapping 2007 CSUMB multibeam-echosounder data in the western part of the map area.

An illumination having an azimuth of 300° and from 45° above the horizon was then applied to the bathymetric surface to create the shaded-relief imagery (sheets 1, 2). In addition, a modified “rainbow” color ramp was applied to the bathymetry data for sheet 1, using reds and oranges to represent shallower depths, and greens to represent greater depths (note that the Offshore of Santa Barbara 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, 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, then the contours were clipped to the boundary of the map area.

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

tones). The differences in backscatter intensity that are apparent in some areas on sheet 3 are due to the different frequencies of mapping systems, as well as different processing techniques.

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 Santa Barbara 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 Santa Barbara 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 Santa Barbara 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, 3, 5, and 6 on sheet 4. These figures highlight the relatively low relief of seafloor features located offshore of the Santa Barbara area.

Video-mosaic images created from digital seafloor video (for example, figs. 4 and 7 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 over 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.

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. 1 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 Santa Barbara 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 shapefiles that have attributes derived from Greene and others (2007).

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

The following six substrate classes are identified in the Offshore of Santa Barbara 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)
- Class V: Anthropogenic material (smooth, hard)
- Class VI: Medium- to coarse-grained sediment (in scour depressions)

The seafloor-character map of the Offshore of Santa Barbara 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. Classes IV and V (rugged and smooth anthropogenic material, respectively; both related to oil platforms and pipes) values were determined on the basis of their visual characteristics and the known location of man-made features. Class VI values (medium- to coarse-grained sediment, in scour depressions) were determined on the basis of their visual characteristics using both shaded-relief bathymetry and backscatter (slight depression in the seafloor, very high backscatter return). The resulting map (gridded at 2 m) was cleaned by hand to remove data-collection artifacts (for example, the trackline nadir).

On the seafloor-character map (sheet 5), the six 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 Santa Barbara map area, only Depth Zones 2 and 3 are present. The slope classes that represent the CMECS slope zones are Slope Class 1 = flat (0° to 5°), Slope Class 2 = sloping (5° to 30°), Slope Class 3 = steeply sloping (30° to 60°), Slope Class 4 = vertical (60° to 90°), and Slope Class 5 = overhang (greater than 90°); in the Offshore of Santa Barbara map area, only Slope Class 1 is present. The final classified seafloor-character raster map image is draped over the shaded-relief bathymetry for the area (sheets 1 and 2) to produce the image shown on the seafloor-character map on sheet 5.

The seafloor-character classification is also summarized on sheet 5 in table 1. Fine- to medium-grained smooth sediment (sand and mud) makes up 98.0 percent (110.0 km^2) of the map area: 21.7 percent (24.3 km^2) is in Depth Zone 2, and 76.3 percent (85.7 km^2) is in Depth Zone 3. Mixed smooth sediment (sand and gravel) and rock (that is, sediment typically forming a veneer over bedrock, or rock outcrops having little to no relief) make up 1.7 percent (1.9 km^2) of the area mapped: 0.9 percent (1.0 km^2) is in Depth Zone 2, and 0.8 percent (0.9 km^2) is in Depth Zone 3. Rock and boulder, rugose (rock outcrops and boulder fields having high surficial complexity) makes up 0.2 percent (0.2 km^2) of the map area: 0.1 percent (0.1 km^2) is in Depth Zone 2, and 0.1 percent (0.1 km^2) is in Depth Zone 3. Rugged anthropogenic material (for example, a pipe) makes up 0.1 percent (0.1 km^2) of the map area: less than 0.1 percent (<0.1 km^2) is in Depth Zone 2, and less than 0.1 percent (<0.1 km^2) is in Depth Zone 3. Smooth, hard anthropogenic material (for example, debris surrounding the pipe) makes up less than 0.1 percent (<0.1 km^2) of the area mapped: less than 0.1 percent (<0.1 km^2) is in Depth Zone 2, and less than 0.1 percent (<0.1 km^2) is in Depth Zone 3. Medium- to coarse-grained sediment (in scour depressions consisting of material that is coarser than surrounding seafloor), present only in Depth Zone 2, makes up less than 0.1 percent (<0.1 km^2) of the map area.

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). Other classes were assigned on the basis of either the observation of anthropogenic features (for example, Classes IV and V) or the observation of one or more of a group of features (for example, Class VI) that includes larger scale bedforms (for example, sand waves), as well as the sediment-filled scour depressions that resemble “rippled scour depressions” of Cacchione and others (1984) and Phillips (2007) and also the “sorted bedforms” of Murray and Thieler (2004), Goff and others (2005), and Trembanis and Hume (2011).

Next, circular buffer areas were created around individual observation points using a 10-m radius to account for layback and positional inaccuracies inherent to the towed-camera system. The radius length is an average of the distances between the positions of sharp interfaces seen on both the video (the position of the ship at the time of observation) and sonar data, plus the distance covered during a 10-second observation period at an average speed of 1 nautical mile/hour. Each buffer, which covers more than 300 m^2, contains approximately 77 pixels. The classified (I, II, III) buffer is used as a mask to extract pixels from the seafloor-character map. These pixels are then compared to the class of the buffer. For example, if the shipboard-video observation is Class II (mixed smooth sediment and rock), but 12 of the 77 pixels within the buffer area are characterized as Class I (fine- to medium-grained smooth sediment), and 15 (of the 77) are characterized as Class III (rock and boulder, rugose), then the comparison would be “Class I, 12; Class II, 50; Class III, 15” (fig. 4–1). If the video observation of

substrate is Class II, then the classification is accurate because the majority of seafloor pixels in the buffer are Class II. The accuracy values in table 4–2 represent the final of several classification iterations aimed at achieving the best accuracy, given the variable quality of sonar data (see discussion in Cochrane, 2008) and the limited ground-truth information available when compared to the continuous coverage provided by swath sonar. Presence/absence values in table 4–2 reflect the percentages of observations where the sediment classification of at least one pixel within the buffer zone agreed with the observed sediment type at a certain location.

The seafloor in the Offshore of Santa Barbara map area is mainly flat with small, local sedimentary-bedrock exposures (Class III). The seabed is predominantly covered by Class I sediment composed of soft, unconsolidated sand and mud. Class II sediment varies from gravel to sediment-covered tar flows. Differentially eroded sedimentary-bedrock outcrops (Class III) are present mainly in the east-southeastern part of the map area, 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). Several anthropogenic features associated with oil production are present, including platforms and pipelines, jetties and groins, and shell mounds beneath platforms.

The classification accuracy of Class I (96 percent accurate; table 4–2) is determined by comparing the shipboard video observations and the classified map. The weaker agreements in Classes II and III (27 percent accurate and 12 percent accurate, respectively) likely are due to the distribution of small, localized rock outcrops and also to 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. The presence/absence accuracy was found to be significant for Classes I and II (98 percent for Class I, and 86 percent for Class II). Only a limited number of observations 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 accuracy is somewhat lower (46 percent) for Class III.

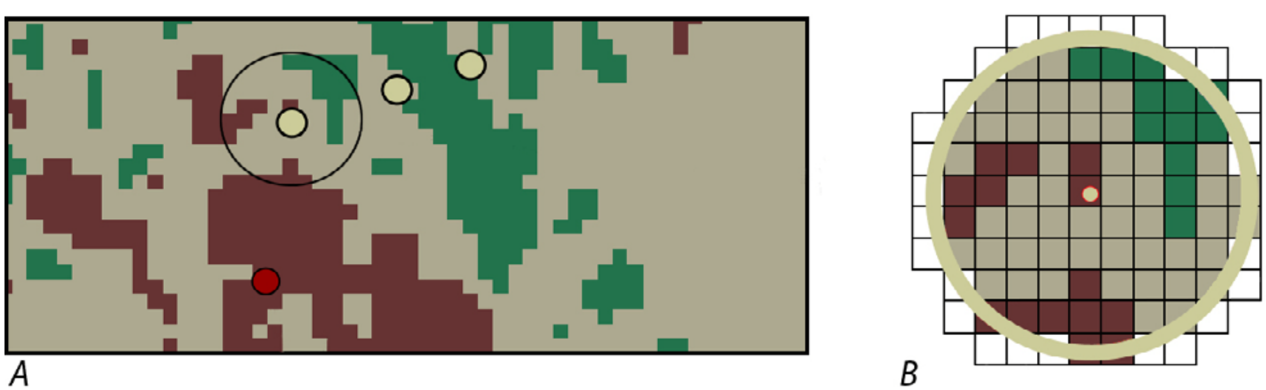

Figure 4–1. Detailed view of ground-truth data, showing accuracy-assessment methodology. *A*, Dots illustrate ground-truth observation points, each of which represents 10-second window of substrate observation plotted over seafloor-character grid; circle around dot illustrates area of buffer depicted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

No video observations were retrieved over the pipe or oil-platform structures (Class IV substrate, rugged anthropogenic feature, and Class V substrate, smooth, hard anthropogenic feature, respectively) in the map area, nor were they retrieved over Class VI substrate (medium- to coarse-grained sediment); therefore, no accuracy assessments were performed for these classes.

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 Santa Barbara 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	sand	low	
sand	mud	low	
sand	sand	low	
			sediment
			ripples
Class II			
cobbles	sand	moderate	
gravel	sand	low	
mud	boulders	low	
mud	boulders	moderate	
rock	mud	low	
rock	rock	low	
sand	boulders	moderate	
sand	cobbles		
sand	cobbles	low	
sand	gravel	low	
sand	rock	low	
sand	rock	moderate	
Class III			
boulders	boulders	moderate	
boulders	mud	moderate	
rock	gravel	moderate	
rock	mud	moderate	
rock	rock	high	
rock	rock	moderate	
rock	sand	moderate	

Table 4–2. Accuracy-assessment statistics for seafloor-character-map classifications in Offshore of Santa Barbara 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	398	96.2	98.2
II—Mixed smooth sediment and rock	29	27.3	86.2
III—Rock and boulder, rugose	24	12.3	45.8
IV—Rugged anthropogenic feature	0	N/A	N/A
V—Smooth, hard anthropogenic feature	0	N/A	N/A
VI—Medium- to coarse-grained sediment (in scour depressions)	0	N/A	N/A

Chapter 5. Ground-Truth Studies for the Offshore of Santa Barbara 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 Santa Barbara map area to collect video and photographic data that would “ground truth” the seafloor. This ground-truth surveying occurred on three separate cruises in 2005, 2006, and 2008. The camera sled was towed 1 to 2 m over the seafloor, at speeds of between 1 and 2 nautical miles/hour. Ground-truth surveys in this map area include approximately 16 trackline kilometers of video and 335 still photographs, in addition to 829 recorded seafloor observations of abiotic and biotic attributes. A visual estimate of slope also was recorded.

During the 2005 and 2006 cruises, a smaller USGS camera sled was used that housed two standard-definition (640×480 pixel resolution) video cameras: one was forward looking, and the other was downward looking. During the 2008 cruise, a larger camera sled was used that housed the two standard-definition 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

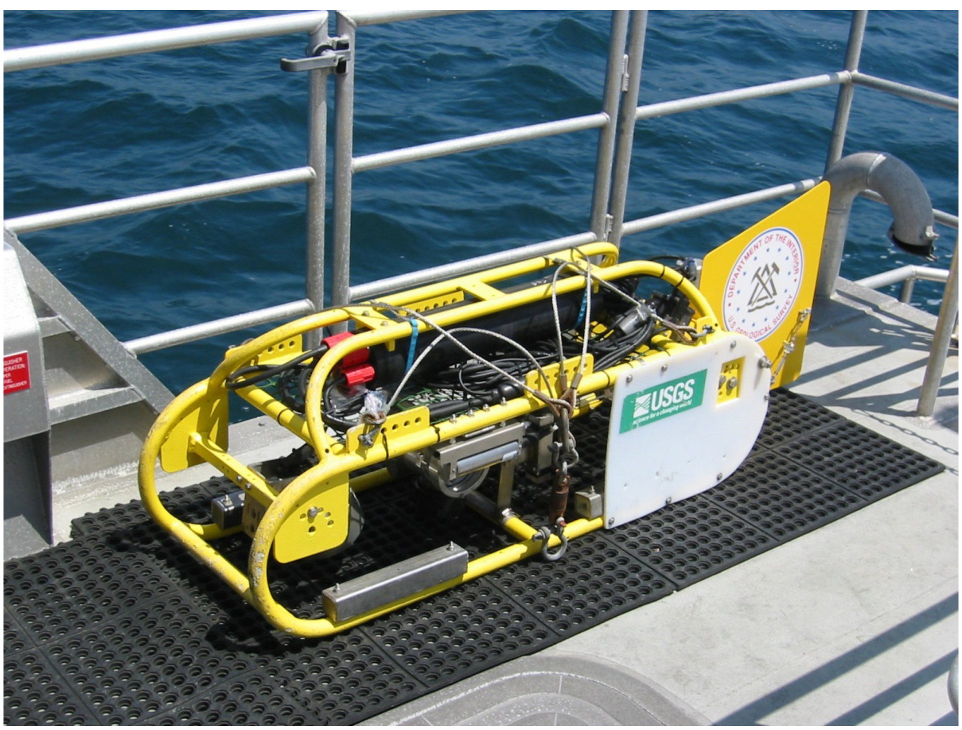

Figure 5–1. Photograph of camera sled used in USGS 2008 ground-truth survey.

the camera is deployed, several different observations are recorded for a 10-second period once every minute, using the protocol of Anderson and others (2007). Observations of primary substrate, secondary substrate, slope, abiotic complexity, biotic complexity, and biotic cover are mandatory. Observations of key geologic features and the presence of key species also are made.

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

Sheet 6 contains a smaller, simplified (depth-zone symbology has been removed) version of the seafloor-character map on sheet 5. On this simplified map, the camera-sled tracklines used to ground-truth-survey the sonar data are shown by aligned colored dots, each dot representing the location of a recorded observation. A combination of the 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 Santa Barbara map area, the surface is covered predominantly by sediment with some differentially eroded bedrock outcroppings offshore of Santa Barbara. The more rugose rock outcrops are surrounded by areas of mixed rock and sediment or flat rock outcroppings.

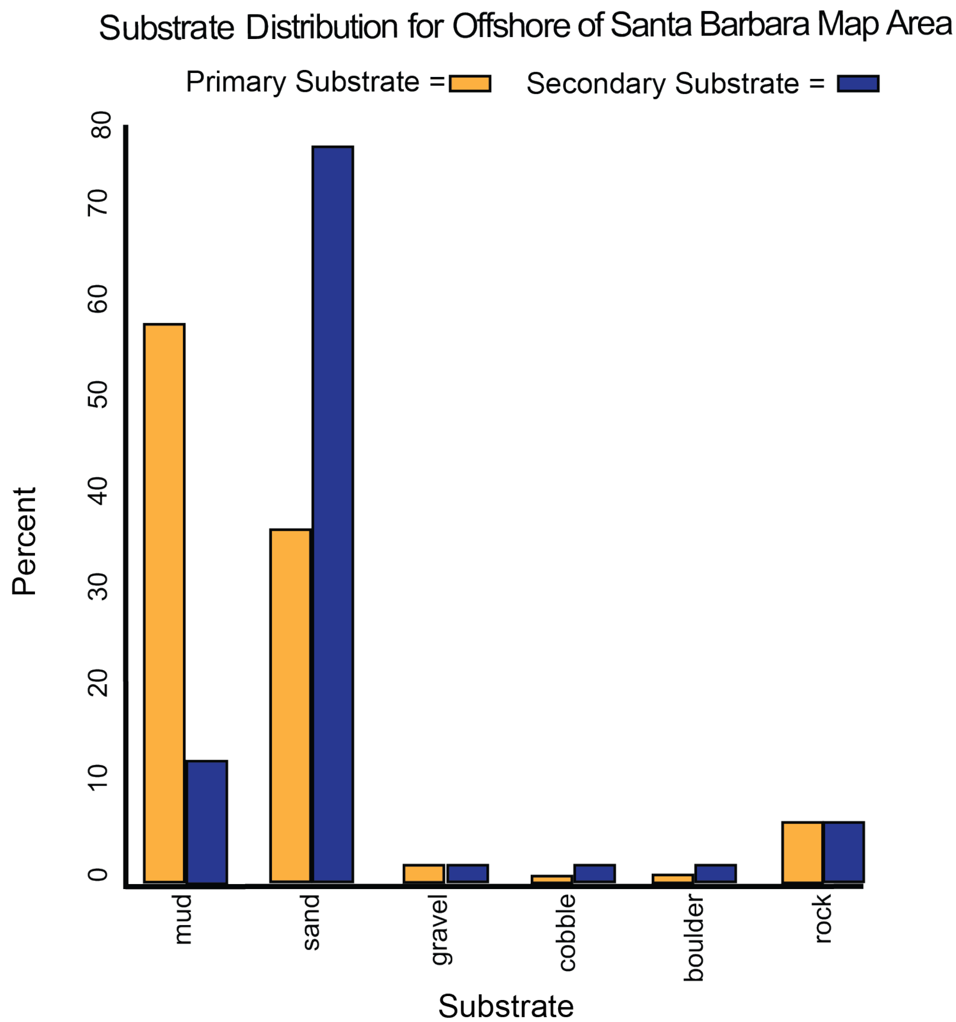

Figure 5–2. Graph showing distribution of primary and secondary substrate determined from video observations in Offshore of Santa Barbara map area.

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

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

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

Backscatter maps (sheet 3) also are essential for developing potential benthic habitat maps. High backscatter is further indication of “hard” bottom, consistent with interpretation as rock or coarse sediment. Low backscatter, indicative of a “soft” bottom, generally indicates a fine-sediment environment. Habitat interpretations 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 (sheet 10). The habitat interpretations on sheet 7 are further informed by the usSEABED bottom-sampling compilation of Reid and others (2006).

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

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

Classifying Potential Marine Benthic Habitats

Potential marine benthic habitats in the Offshore of Santa Barbara 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 Santa Barbara 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 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 Santa Barbara map area are 26 potential marine benthic habitat types. These habitat types range from primarily soft, unconsolidated sediment (mud to sand and gravel) to hard bedrock exposures (flat carbonate substrate; asphalt (tar) mounds; differentially eroded, well-bedded sedimentary outcrops). Sedimentary-bedrock outcrops (some of which are partly covered with sediment to produce a hard-soft mixed habitat type), as well as pockmarks, rills, and possible hummocky tar flows, complete the variety of habitats identified in the map area. Significant anthropogenic features associated with oil production, such as platforms, pipelines, and shell mounds beneath platforms, as well as riprap and a shipwreck, all produce artificial habitats for rockfish (*Sebastes* spp.). Trawl marks are also present as anthropogenic features.

The soft, unconsolidated sediment habitat, which includes pockmarks and inferred sediment-covered tar flows, covers 97.41 km^2 of the map area, representing 86.6 percent of all the potential habitat types identified. Sediment-covered bedrock, which includes the hard-soft mixed habitat type, covers 11.84 km^2 (10.5 percent). Hard bedrock exposures cover 3.08 km^2 (2.7 percent), whereas anthropogenic features cover about 0.17 km^2 (<0.15 percent). The mix of potential marine benthic habitat types provides the varied relief, in addition to the rugosity and substrate hardness, that contribute to the concentration of a diverse ecosystem within an otherwise homogeneous, soft, unconsolidated sediment habitat.

Of special interest in the Offshore of Santa Barbara map area is the role of fluid flowing up to the seafloor from petroleum reservoirs at depth, which is inferred to have caused the formation of locally exposed hard, carbonate-cemented sediment substrate, carbonate mounds, pockmarks, and tar or asphalt flows. Notably, an extensive (7.09 km^2) area of carbonate hardground (Sme_c/l/u), locally covered with sediment, is exposed about 5 km offshore in the southwestern part of the map area, providing potential habitat for sessile organisms. In addition, one prominent lobe (Ssl_h/t/u?) in the map area may be a sediment-covered tar flow. This possible tar flow could have its source in an upslope tar-drain depression now covered by sediment (Ss(s/m)h_r/u), 0.37 km^2 in area, which is located on the northwest flank of a prominent, differentially eroded, east-west-trending bedrock platform (Shd_c/d).

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

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

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

The maps on sheet 9 show the following interpretations, which are based on the seismic-reflection profiles on sheet 8: the thickness of the uppermost sediment unit; the depth to base of this uppermost unit; and both the local and regional distribution of faults and earthquake epicenters (data from 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, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12) were collected in 2007 on U.S. Geological Survey (USGS) cruise Z–3–07–SC (Sliter and others, 2008). Single-channel seismic-reflection data were acquired using two different sources, the EdgeTech 512 chirp (figs. 3, 4, 5, 7, 9, 11) and the SIG 2Mille minisparker (figs. 1, 2, 6, 8, 12). The EdgeTech 512 chirp subbottom-profiling system consists of a source transducer and an array of receiving hydrophones 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 SIG minisparker system used a 500-J high-voltage electrical discharge fired 1 to 4 times per second, which, at normal survey speed of 4 to 4.5 nautical miles/hour, gives a data trace every 0.5 to 2.0 m of lateral distance covered. The data were digitally recorded in standard SEG-Y 32-bit floating-point format, using Triton Subbottom Logger (SBL) software that merges seismic-reflection data with differential GPS-navigation data. After the survey, a short-window (20 ms) automatic gain control algorithm was applied to both the chirp and minisparker data, and a 160- to 1,200-Hz bandpass filter was applied to the minisparker 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.

Figure 10 on sheet 8 shows a deep-penetration, migrated, multichannel seismic-reflection profile collected in 1984 by WesternGeco on cruise W–37–84–SC. This profile and other similar data were collected in many areas offshore of California in the 1970s and 1980s when these areas were considered a frontier for oil and gas exploration. Much of these data have been publicly released and are now archived at the U.S. Geological Survey National Archive of Marine Seismic Surveys (U.S. Geological Survey, 2009). These data were acquired using a large-volume air-gun source that has a frequency range of 3 to 40 Hz and recorded with a multichannel hydrophone streamer about 2 km long. Shot spacing was about 30 m. These data can resolve geologic features that are 20 to 30 m thick, down to subbottom depths of about 4 km.

Seismic-Reflection Imaging of the Continental Shelf

Sheet 8 shows seismic-reflection profiles in the Offshore of Santa Barbara map area, which is characterized by a relatively flat (less than 1°), moderately deep (75 m or less), wave-cut shelf with local relief associated with bedrock uplifts (see sheets 1, 2, 10). This shelf is underlain by variably thick (0 to about 14 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 (as much as 15 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; Stanford and others, 2011).

The sediments deposited during this latest Pleistocene and Holocene sea-level rise are shaded blue in the high-resolution seismic-reflection profiles on sheet 8 (figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12), and their thickness is shown on sheet 9. In the minisparker profiles (figs. 1, 2, 6, 8, 12 on sheet 8), these strata are typically characterized by parallel, low- to moderate-amplitude, low- to high-frequency, continuous to moderately continuous reflections (terminology from Mitchum and others, 1977). In the chirp seismic-reflection profiles (figs. 3, 4, 5, 7, 9, 11 on sheet 8), this stratigraphic interval commonly is “acoustically transparent” (that is, lacking internal reflections). The presence and continuity of seismic reflections in this upper 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 Summerland oil field (see, for example, Kunitomi and others, 1998) and near the crests of 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, consist of thin marginal marine deposits (especially where the unit is thickest). These strata were reworked and then covered by nearshore and shelf sediments as sea level rose and the shoreline migrated both landward and upward. The upper part of this unit must consist of shelf deposits that are similar to the sediments found 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 a high-amplitude reflection. Post-LGM sediment onlapping of local uplifts (for example, figs. 3, 9) is common. 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 45 m offshore of Santa Barbara (see, for example, figs. 8, 9) and of about 34 m offshore of Montecito (see, for example, figs. 4, 7). Given uplift rates from nearby coastal terraces (Trecker and others, 1998; Keller and Gurrola, 2000, their fig. 6), these depths are consistent with formation during late oxygen-isotopic stage 3, about 40 to 25 ka. Alternatively, they could also have formed 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 as much as 15 m per thousand years during meltwater pulse 1b, about 10,000 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.

Geologic Structure and Recent Deformation

Seismic-reflection profiles in the Offshore of Santa Barbara map area (sheet 8) show significant folding and faulting. The east-west-striking, south-dipping Rincon Creek Fault Zone (figs. 2, 7, 9, 12 on sheet 8), which extends into the map area from the east, forms the north edge of a northwest-trending uplift of complexly deformed Miocene Monterey Formation, due south of Santa Barbara (see sheet 10);

similarly, it forms the north edge of a bedrock uplift in the Offshore of Carpinteria map area to the east (see Johnson and others, 2013). Within the Offshore of Santa Barbara map area, the fault zone is "blind" because it does not appear to rupture to the surface or to clearly offset the upper Pleistocene and Holocene stratigraphic unit. Instead, it is characterized by a zone of deformation that includes an upward-narrowing asymmetric syncline that has a gently south-dipping north limb and a more steeply north-dipping south limb (figs. 7, 9, 12 on sheet 8). The steep, north-dipping south limb forms the margin of a sedimentary basin inferred to be filled by the Pleistocene Santa Barbara and Casitas Formations (Redin, 2005). An interpretation on sheet 8 (fig. 2) shows about 2.0 to 2.5 m of folding-related uplift in the latest Pleistocene and Holocene stratigraphic unit, but as much as 12 m of uplift is plausible. Onland to the west, the trace of the Rincon Creek Fault Zone probably bends more northwestward and merges with the Lavigia Fault, which similarly forms a local boundary between the Monterey Formation and the Santa Barbara Formation (Minor and others, 2009).

The steeply dipping north strand of the Red Mountain Fault Zone also extends westward from the Offshore of Carpinteria map area (Johnson and others, 2013) into the Offshore of Santa Barbara map area, where it is coincident with the axis of a prominent tight syncline (figs. 7, 11 on sheet 8; see also, sheet 10). Although the syncline can be mapped across the entire map area, faulting in the shallow subsurface appears to die out about 7 km east of the west edge of the map. The east-west-striking, north-dipping south strand of the Red Mountain Fault Zone extends south of the map area, and it appears to die out in the shallow subsurface south of Montecito (south of the map area). Farther south, the east-west-striking, north-dipping Pitas Point–North Channel Fault (fig. 10 on sheet 8) cuts across the slope about 2 to 5 km south of the map area.

Both the Red Mountain and the Rincon Creek Fault Zones in the map area are inferred to have complex structure at depth (characterized by numerous splays) on the basis of the irregular character of their near-surface folding; closely spaced seismic-reflection profiles document variable fold presence, geometry, length, amplitude, continuity, and wavelength (figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12 on sheet 8). The cross section of Redin (2005) suggests that the south-dipping Rincon Creek Fault merges at depth with splays of the north-dipping Red Mountain Fault to form a zone characterized by both north-south contraction and left-lateral displacement.

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 Santa Barbara map area (~M4.1) occurred on 3/10/1986 near the west edge of the map.

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 Santa Barbara 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 product. 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 data set 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 Santa Barbara map area, thickness data (Map B on sheet 9) reveal that the post-LGM section has a mean thickness of just 3.4 m. Sediment is either notably lacking or it forms only a thin veneer over bedrock outcrops on the outer shelf. These outer shelf outcrops are a continuation of the east-west-trending uplifts that are present between the north and south strands of the Red Mountain Fault (Johnson and others, 2013). The thickness map also reveals a shallow trough north of the Red Mountain Fault Zone and south of the uplift associated with the Rincon Creek Fault Zone. This trough includes a “bedrock saddle” due south of Santa Barbara, east of which sediment thickens rapidly to more than 10 m. West of the saddle, sediment typically is 1 to 5 m thick but increases to more than 10 m in the nearshore along the west edge of the map area. Figure 3 on sheet 8 shows that this nearshore sediment “thick” has positive seafloor relief and delta-front morphology, including a relatively flat (about 0.6°) upper surface and a steeper (about 2.4°) seaward-dipping front. This feature is aligned with, and slightly west of, a network of streams (for example, Atascadero Creek; fig. 1–2) that drain into

Goleta Slough (about 2 km west of the map area), and these coastal watersheds are the inferred source of the sediments that make up this small “delta-mouth bar.”

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 Santa Barbara 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 thickness in Offshore of Santa Barbara map area			
Offshore of Santa Barbara map area	103.6	3.4	350.2

Chapter 8. Geologic and Geomorphic Map of the Offshore of Santa Barbara Map Area (Sheet 10)

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

Geologic and Geomorphic Summary

Marine geology and geomorphology were mapped in the Offshore of Santa Barbara 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 (1986a,b) and Minor and others (2009). Unit ages, which are derived from these sources, reflect local stratigraphic relations.

The offshore part of the map area largely consists of a relatively shallow (less than 75 m deep), gently offshore-dipping (less than 1°) shelf underlain by sediments derived primarily from relatively small coastal watersheds that drain the Santa Ynez Mountains. Shelf deposits are primarily sand (unit Qms) at water depths less than about 35 to 50 m and, at depths greater than about 35 to 50 m, are the more fine-grained sediments (very fine sand, silt, and clay) of unit Qmsf. 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.

Coarser grained deposits (coarse sand to boulders) of unit Qmsc, which are recognized on the basis of their high backscatter and, in some cases, their moderate seafloor relief (sheets 1, 2, 3), are found most prominently in a large (about 0.75 km^2) lobe that is present from about 1,800 to 3,600 m offshore of the mouth of Arroyo Burro, in water depths of about 36 to 65 m. The lobe is inferred to consist of coarse-grained sediment (coarse sand to boulders) that is resistant to erosion. Although these coarse-grained deposits almost certainly are derived from Arroyo Burro, the lobe could represent either the underflow deposits of late Holocene floods or a relict geomorphologic feature, having been deposited in shallower marine deltaic (or even alluvial?) environments at lower sea levels in the latest Pleistocene and early Holocene. Unit Qmsc also is present in shallower water (depths of about 10 to 20 m), most notably in a small area (approximately 0.09 km^2) that extends offshore from Montecito Creek, in the eastern part of the map area.

The presence of coarser grained sediment (coarse sand and possibly gravel) also is inferred in shallower water (depths of 10 to 20 m) offshore from Arroyo Burro, but these deposits are mapped as unit Qmss because they are found within arcuate scour depressions that have been referred to as "rippled scour depressions" (see, for example, Cacchione and others, 1984; Phillips, 2007) or "sorted bedforms" (see, for example, Murray and Thieler, 2004; Goff and others, 2005; Trembanis and Hume, 2011). Although the general area in which Qmss scour depressions are found is not likely to change substantially, the boundaries of the unit(s), as well as the locations of individual depressions and their intervening flat sand sheets, likely are ephemeral, changing during significant storm events.

Hydrocarbon-seep-induced topography, which is present most prominently along the axis of anticlines, includes many features (described by Keller and others, 2007) along the trend of the Mid-

Channel Anticline, about 10 km south of the map area in the Santa Barbara Channel. Geologic map units associated with hydrocarbon emissions in the map area include grouped to solitary pockmarks (unit Qmp) and asphalt (tar) deposits (unit Qas), as well as areas of undifferentiated hydrocarbon-related features (unit Qhfu) that probably include a mix of mounds, mud volcanoes, pockmarks, carbonate mats, and other constructional and erosional “seabed forms” (see Keller and others, 2007), all of which are superimposed on consolidated, undivided Miocene and Pliocene bedrock (unit Tbu).

Offshore bedrock exposures are assigned to the Miocene Monterey Formation (unit Tm) and to the undivided Miocene and Pliocene bedrock unit (Tbu), primarily on the basis of extrapolation from the onland geologic mapping of Minor and others (2009), as well as the geologic cross sections of Redin (2005). These cross sections, which are constrained by industry seismic-reflection data and petroleum well logs, suggest that a considerable part of the undivided bedrock unit may belong to the Pliocene and Pleistocene Pico Formation. Bedrock is, in some places, overlain by a thin (less than 1 m?) veneer of sediment, recognized on the basis of high backscatter, flat relief, continuity with moderate- to high-relief bedrock outcrops, and (in some cases) high-resolution seismic-reflection data; these areas, which are mapped as composite units Qms/Tbu or Qms/Tm, are interpreted as ephemeral sediment layers that may or may not be continuously present, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term climate cycles. The relative proportions of all offshore map units are shown in table 8–1.

The Santa Barbara Channel region, including the map area, has a long history of petroleum production (Barnum, 1998). The Monterey Formation is the primary petroleum-source rock in the Santa Barbara Channel, and the Pico Formation is one of the primary petroleum reservoirs. The bedrock units typically are exposed in structural highs that include uplifts associated with the partly blind(?), south-dipping Rincon Creek Fault Zone and the outer shelf anticlinal uplift that developed above the south strand of the Red Mountain Fault in the southwestern part of the map area.

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

Map Unit	Area (m^2)	Area (km^2)	Percent of total area
Artificial fill unit			
af	290,044	0.29	0.27
Marine sedimentary units			
Qas, Qas?	62,887	0.06	0.06
Qms	58,991,008	58.99	55.22
Qmp	16,765	0.02	0.02
Qmsc	1,645,599	1.65	1.54
Qmsf	31,424,542	31.42	29.41
Qmss	284,552	0.28	0.27
Total, sedimentary units	92,425,352	92.43	86.51
Marine bedrock and (or) shallow bedrock units			
Qms/Tbu	7,944,152	7.94	7.44
Qhfu	2,250,609	2.25	2.11
Tbu, Tbu?	3,104	0.00	0.00
Total, undifferentiated bedrock units	10,197,865	10.20	9.55
Qms/Tm	346,412	0.35	0.32
Tm	3,575,796	3.58	3.35
Total, Monterey Formation	3,922,209	3.92	3.67
Total, all bedrock units	14,120,073	14.12	13.22
Total, Offshore of Santa Barbara map area	106,835,469	106.84	100.00

The Offshore of Santa Barbara 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 (Fisher and others, 2009). This province has undergone significant north-south compression since the Miocene, and recent GPS data suggest north-south shortening of about 6 mm/yr (Larson and Webb, 1992). The active, east-west-striking Red Mountain and Rincon Creek Faults and their related folds are some of the structures on which this shortening occurs. This fault system, in aggregate, extends for about 100 km through the Ventura and Santa Barbara Basins and represents an important earthquake hazard (see, for example, Fisher and others, 2009). Very high uplift rates of onland marine terraces from More Mesa (2.2 mm/yr), in the western part of the map area, to Summerland (0.7 mm/yr), a few kilometers east of the map area, are further indication of rapid shortening in this region (Keller and Gurrola, 2000).

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/Tm indicates that thin sheet of Qms overlies Tm)]

af **Artificial fill (late Holocene)**—Rock, sand, and mud; placed and (or) dredged; associated with Santa Barbara Harbor. Also includes seafloor substantially modified by human activity

Qms **Marine nearshore and shelf deposits (late Holocene)**—Mostly sand; ripple marks common. Found on gently seaward-dipping (less than 1°) surface that extends from nearshore to water depths of about 35 to 70 m

Qmsc **Coarse-grained marine nearshore and shelf deposits (late Holocene)**—Predominantly sand, gravel, and boulders; forms large, low-relief lobe about 1,800 m offshore of mouth of Arroyo Burro, in water depths of about 36 to 65 m. Also found as small patches on gently seaward-dipping surface offshore of Montecito Creek, in water depths less than about 20 m. Recognized primarily on basis of high backscatter and low to moderate relief

Qmsf **Fine-grained marine shelf deposits (late Holocene)**—Mostly mud to muddy sand; commonly bioturbated; found on gently seaward-dipping (less than 1°) surface at depths that range from about 35 to 70 m

Qmss **Marine shelf scour depressions (late Holocene)**—Inferred to be coarse sand and possibly gravel; found as single depressions or in fields of depressions interspersed with elevated shelf sediments (unit Qms). Occupies three small fields (0.025 to 0.15 km^2) a few hundred meters east of mouth of Arroyo Burro (fig. 1–2) at water depths of 10 to 20 m. Depressions, which typically are 25 to 50 cm deep, have sharp boundaries on shoreward edge that grade to diffuse, low-relief boundaries on offshore edge. In map area, backscatter data and direct camera observations show small intensity contrasts that suggest that depressions are filled with sand that is coarser than intervening elevated sandy shelf deposits. General area in which unit is found is not likely to change substantially, but boundaries of unit(s) and locations of individual depressions (and intervening flat sheets) likely are ephemeral, changing during significant storm events

Qmp **Marine pockmarks (late Holocene)**—Sand and mud, in circular to elliptical pockmarks. Pockmarks, which are solitary or grouped, range in size from 50 to 150 m along their long axes, typically are 20 to 40 cm deep, and commonly have central cone that has raised relief of as much as 150 cm

Qas **Asphalt deposits (Holocene)**—Asphalt (tar); weathered and biodegraded oil derived from underlying or nearby natural hydrocarbon seeps. Most commonly found along or adjacent to faults or anticlinal axes. Has local high relief and backscatter

Qhfu **Mixed hydrocarbon-seep-related features and marine deposits (Holocene)**—Hydrocarbon-seep-related features (see Keller and others, 2007, their table 1) that have irregular seafloor relief and high backscatter; probably includes mixed and coalescing mounds, pockmarks, carbonate mats, and mud volcanoes and cones. Superimposed on bedrock; most commonly found along or adjacent to faults or anticlinal axes

Tbu **Bedrock, undivided (Pliocene and Miocene)**—Consists of undivided strata of the Pico, Sisquoc, and Monterey Formations. 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

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units are compiled from Dibblee (1986a,b) and Minor and others (2009); unit ages, which are 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

Qes **Coastal-estuarine deposits (late Holocene)**—Locally organic-rich clay, silt, and subordinate sand. Mapped primarily in tidally influenced environments

Qa **Channel alluvium (late Holocene)**—Unconsolidated sediments, primarily pebble to boulder gravel, in floors and banks of modern stream channels. Commonly incised as much as 5 m into alluvial deposits of associated floodplain (unit Qyf)

Qas **Asphalt deposits (Holocene)**—Black asphalt (tar) that represents weathered and biodegraded oil derived from nearby natural hydrocarbon seeps. Found along shoreline near west edge of map area

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

Qyd **Debris-flow deposits (Holocene and late Pleistocene)**—Massive, weakly consolidated rock-debris breccia; derived from upslope rock units. Mainly located along lower flanks of Santa Ynez Mountains

Qc **Colluvium (Holocene and late Pleistocene)**—Poorly consolidated, poorly stratified, and poorly sorted sediments that mantle gentle to moderate slopes; formed by weathering and downslope movement of bedrock debris

Qls **Landslide deposits (Holocene to middle Pleistocene)**—Deposits of diverse slope-movement processes; ranges from poorly sorted and disrupted mixtures of rock fragments and soil to relatively intact bedrock slump blocks. Thickness of largest landslide deposits, as much as 60 m

Qomp **Marine-terrace deposits (late Pleistocene)**—Weakly to moderately consolidated, variably stratified, fossiliferous gravel, sand, and silt; deposited as marine intertidal, beach, and estuarine deposits; commonly overlain by nonmarine eolian, alluvial, and colluvial deposits. Marine-terrace deposits rest on elevated marine wave-cut platforms and form single terraces or flights of terraces that, in Santa Barbara coastal area, range in elevation from 10 to 90 m (30–300 ft) and in age from 105,000 (oxygen-isotope substage 5c) to 45,000 (substage 3a) years old

Qoa2 **Alluvial deposits (late Pleistocene)**—Weakly consolidated, stratified silt, sand, and gravel; forms low, rounded, moderately dissected terraces and piedmont alluvial fans. Present at elevations higher than modern coastal-piedmont surface. Thickness, may exceed 20 m locally

Qoa1 **Older alluvial deposits (late and middle Pleistocene)**—Moderately consolidated, crudely stratified, poorly sorted sand and sandstone, gravel, conglomerate, and breccia, as well as rare interbeds of clay, silt, and mudstone; makes up proximal to distal facies of alluvial fans shed from Santa Ynez Mountains. Unit forms dissected, gently south-sloping, elevated terraces, interfluvial caps, and other erosional remnants. Thickness, as much as 35 m

Qca **Casitas Formation (late and middle Pleistocene)**—Nonmarine, moderately to well-consolidated siltstone and silt, sandstone and sand, and conglomerate and gravel; deposited mainly as alluvium, likely shed from Santa Ynez Mountains. Conglomerate and gravel contain greater percentage of Sespe Formation–derived clasts than older alluvial deposits (unit Qoa1) mapped nearby. Maximum exposed thickness, 50 m in Santa Barbara coastal region

Qbx **Shale-clast sedimentary breccia (middle Pleistocene)**—Nonmarine breccia and conglomerate; mostly composed of clasts of shale and mudstone derived from the Monterey Formation. Breccia inferred to be locally derived paleocolluvium. Thickness, locally exceeds 10 m

Qsb **Santa Barbara Formation (middle and early Pleistocene)**—Chiefly marine, friable, bioturbated and massive sandstone; pale gray, pale buff, and pale tan; includes subordinate interbeds and intervals of shale, siltstone, and silty to clayey sandstone. Contains diverse assemblage of marine invertebrate fossils. Rare conglomeratic lenses become more common upsection, and uppermost part of unit locally interfingers with nonmarine conglomerates of the older alluvial deposits unit (Qoa1) or the Casitas Formation (unit Qca)

Unnamed sedimentary rocks east of Goleta Pier (Pleistocene and Pliocene?)—Marine conglomerate, sandstone, siltstone, and mudstone. Mapped as the following three distinct units:

Qcg **Conglomeratic unit (middle and early Pleistocene)**—Conglomerate, sandstone, siltstone, and mudstone; probably deposited in ancient submarine canyon eroded into underlying Pleistocene and Pliocene rocks (units Qss, Tsq). Contains marine fossils. Conglomerate contains clasts derived from the Sisquoc Formation (unit Tsq) and the Monterey Formation (units Tmu, Tmm, Tml), as well as older units. Width of paleo–submarine channel exposed in sea cliff is about 610 m; minimum thickness in channel axis, 33 m

Qss **Sandstone-rich unit (early Pleistocene?)**—Laminated and bioturbated sandstone, siltstone, and subordinate mudstone and conglomerate. Contains marine fossils and clasts derived from the Sisquoc Formation (unit Tsq) and the Monterey Formation (units Tmu, Tmm, Tml). Exposed thickness, 45 to 60 m

QTst **Siltstone unit (early Pleistocene and late Pliocene?)**—Massive and extensively bioturbated siltstone, mudstone, and silty sandstone. Contains marine fossils. Exposed thickness, about 45 m

Tsq **Sisquoc Formation (early Pliocene and late Miocene)**—Marine, tan- to white-weathering diatomaceous mudstone and shale, conglomerate, and subordinate dolomite. Distinguished by thick beds of conglomerate containing angular clasts (commonly as much as 1 m across; some blocks as large as 10 m) derived from the Monterey Formation. Both base and top are erosional unconformities

Monterey Formation (Miocene)—Marine, predominantly well-bedded, siliceous and calcareous mudstone and shale, with subordinate porcelanite and dolomite. Contains abundant microfossils. Maximum composite thickness of the Monterey Formation in this area estimated to be about 830 m. The Monterey Formation is divided into the following three subunits, which are distinguished on basis of stratigraphic position, lithology, and age:

Tmu **Upper siliceous unit (late Miocene)**—Mainly white- to tan-weathering diatomaceous mudstone and shale, with subordinate dolomite and porcelanite. Thickness in Santa Barbara coastal region ranges from about 50 to 250 m

Tmm **Middle shale unit (late and middle Miocene)**—White-weathering shale, mudstone, dolomite, porcelanite, phosphorite, and subordinate tuff. Thickness in Santa Barbara coastal region estimated to range from 70 to 180 m

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 exhibits intraformational deformation (including breccia) that may have formed by gravitational slumping shortly after deposition. Thickness, as much as 250 m

Tr **Rincon Shale (early Miocene)**—Marine, primarily massive and thick-bedded, light-brown-weathering mudstone, with subordinate dolomite, siliceous shale, sandstone, and tuff. Mudstone is bioturbated, massive, and pervasively hackly fractured; locally, contains abundant microfossils. Single or multiple white-weathering tuff layers limited to upper 10 m of unit. Thickness ranges from about 400 to 460 m

Tv **Vaqueros Formation (late Oligocene)**—Shallow-marine, massive, 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 containing abundant fossil-shell fragments. Within Santa Barbara coastal region, thickness varies from about 75 to 150 m

Sespe Formation (Oligocene and late Eocene)—Interbedded nonmarine, fluvial, maroon, reddish-brown, and greenish- to pinkish-gray sandstone, siltstone, mudstone, and conglomerate. In Santa Barbara coastal region, divided into three subunits that are distinguished mainly by differences in stratigraphic position, lithology, provenance, and age. Intraformational unconformity, which represents depositional hiatus lasting much or all of early Oligocene time, separates lower (Tspl) and middle (Tspm) subunits. Composite thickness in Santa Barbara coastal region ranges from about 700 to more than 1,500 m

Tspu **Upper sandstone and mudstone unit (late Oligocene)**—Interbedded sandstone, siltstone, and mudstone that weather to various shades of maroon, buff, pale green, tan, and gray; proportions of different sedimentary rock types vary both laterally and vertically throughout section. Sandstones commonly are broadly lenticular, laminated, and thin to thick bedded. Thickens eastward across map area from about

500 to more than 1,000 m

Tspm **Middle conglomerate and sandstone unit (Oligocene)**—Interbedded conglomerate, sandstone, and mudstone; weathers to various shades of maroon, tan, and pale-greenish gray; proportions of different sedimentary rock types vary both laterally and vertically throughout section. Polymict conglomerate clasts include abundant chert and lithic sandstone, likely derived from Franciscan Complex source terranes. As much as 340 m thick in Santa Barbara coastal region

Tspl **Lower conglomerate and sandstone unit (early? Oligocene and late Eocene)**—Interbedded conglomerate, conglomeratic sandstone, sandstone, mudstone, and minor shale; mostly weathers to various distinctive shades of salmon gray, reddish gray, pale-pinkish gray, and tan; proportions of different sedimentary rock types vary both laterally and vertically throughout section. Resistant sandstones and conglomerates form hogbacks. Sandstones commonly are arkosic, and polymict conglomerates contain abundant rounded quartzitic, granitoid, metamorphic, and volcanic clasts, likely derived from Mojave Desert source terranes

Tcw **Coldwater Sandstone (late? and middle Eocene)**—Shallow-marine, thin- to thick-bedded sandstone, which weathers to distinctive pale shades of buff, yellow, tan, and brown, and subordinate gray, olive-gray, and greenish-gray siltstone, shale, and mudstone interbeds and thin intervals; resistant sandstone beds form hogbacks where steeply dipping; upper part of unit locally is conglomeratic and rich in fossil oyster shells. Within Santa Barbara coastal region, unit is about 750 to 1,000 m thick

Tcw-sh **Shale unit (late? and middle Eocene)**—Fine-grained, bedded siltstone and shale, with sandstone interbeds. As much as 240 m thick

Tcd **Cozy Dell Shale (Eocene)**—Marine, dark- to light-gray, silty micaceous shale and sandstone, with interbeds of shale. Thickness, as much as 600 m in Santa Barbara coastal region

Tma **Matilija Sandstone (Eocene)**—Marine, tan arkosic sandstone, with thin partings of gray micaceous shale. Thickness, as much as 540 m in Santa Barbara coastal region

Tj **Juncal Formation (Eocene)**—Marine, dark-gray to gray-white shale and sandstone. Thickness, as much as 1,100 m in Santa Barbara coastal region

Kush **Jalama Formation (Late Cretaceous)**—Predominantly marine, dark-gray to black, micaceous clay shale, with minor hard, tan sandstone interbeds (Dibblee, 1950, 1981). Thickness, as much as 700 m in Santa Barbara coastal region

Chapter 9. Predictive Distribution of Benthic Macro-Invertebrates for the Offshore of Santa Barbara 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 (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 Santa Barbara map area is predominantly Class I (unconsolidated sediment); in addition, a large reef made up of Class II (mixed habitat) and Class III (rugose rock) is present beyond the Santa Barbara Harbor (sheet 5; see also, chapter 4 in this pamphlet). Cup corals (Map D on sheet 11), a benthic cnidarian typically found on rocky habitat, have a moderate to high probability of occurrence in areas where suitable habitat is present. Hydroids (Map C on sheet 11), another benthic cnidarian found on rocky habitat, have a low probability of occurrence in the area of the large reef beyond Santa Barbara Harbor; 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 of 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 Santa Barbara map area, brittle stars have a moderate probability of occurrence 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.

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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.

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.

Cacchione, D.A., Drake, D.E., Grant, W.D., and Tate, G.B., 1984, Rippled scour depressions of the inner continental shelf off central California: Journal of Sedimentary Petrology, v. 54, p. 1,280–1,291.

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.

Chappell, J., 1983, A revised sea-level record for the last 300,000 years from Papua, New Guinea: Search, v. 14, p. 99–101.

Chappell, J., and Shackleton, N.J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Clarke, K.C., and Hemphill, J.J., 2002, The Santa Barbara oil spill—A retrospective, *in* Danta, D., ed., Yearbook of the Association of Pacific Coast Geographers: Honolulu, University of Hawai'i Press, v. 64, p. 157–162.

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., 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., 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, volume II: U.S. Geological Survey Open-File Report 2005–1170, available at http://pubs.usgs.gov/of/2005/1170/.

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, volume 1: U.S. Geological Survey Open-File Report 03–85, available at http://geopubs.wr.usgs.gov/open-file/of03-85/.

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.

Dahlen, M.Z., 1992, Sequence stratigraphy, depositional history, and middle to late Quaternary sea levels of the Ventura shelf, California: Quaternary Research, v. 38, p. 234–245.

Dartnell, P., Finlayson, D., Conrad, J.E., Cochrane, G.R., and Johnson, S.Y., 2009, Bathymetry and acoustic backscatter—Northern Santa Barbara Channel, southern California: USGS Open-File Report 2009–1289, available at http://pubs.usgs.gov/of/2009/1289/.

Dibblee, T.W., Jr., 1950, Geology of southwestern Santa Barbara County, California—Point Arguello, Lompoc, Point Conception, Los Olivos, and Gaviota quadrangles: California Division of Mines and Geology Bulletin 150, 95 p.

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

Dibblee, T.W., Jr., 1986a, Geologic map of the Carpinteria quadrangle, Santa Barbara County, California: Santa Barbara, Calif., Dibblee Geological Foundation Map DF–04, scale 1:24,000.

Dibblee, T.W., Jr., 1986b, Geologic map of the Santa Barbara quadrangle, Santa Barbara County, California: Santa Barbara, Calif., Dibblee Geological Foundation Map DF–06, scale 1:24,000.

Drake, D.E., 1972, Distribution and transport of suspended matter, Santa Barbara Channel, California: Los Angeles, University of Southern California, Ph.D. dissertation, 358 p.

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.

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., 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.

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.

Goff, J.A., Mayer, L.A., Traykovski, P., Buynevich, I., Wilkens, R., Raymond, R., Glang, G., Evans, R.L., Olson, H., and Jenkins, C., 2005, Detailed investigations of sorted bedforms or “rippled scour depressions,” within the Martha’s Vineyard Coastal Observatory, Massachusetts: Continental Shelf Research, v. 25, p. 461–484.

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., 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.

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.

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.

Johnson, S.Y., Ritchie, A.C., Seitz, G.G., Phillips, E.L., and Gutierrez, C.I., 2013, Offshore and onshore geology and geomorphology, Offshore of Carpinteria map area, California, *sheet 10 in* Johnson, S.Y., Dartnell, P., Cochrane, G.R., Golden, N.E., Phillips, E.L., Ritchie, A.C., Kvitek, R.G., Greene, H.G., Endris, C.A., Seitz, G.G., Sliter, R.W., Erdey, M.D., Wong, F.L., Gutierrez, C.I., Krigsman, L.M., Draut, A.E., and Hart, P.E. (S.Y. Johnson and S.A. Cochran, eds.), California State Waters Map Series—Offshore of Carpinteria, California: U.S. Geological Survey Scientific Investigations Map 3261, pamphlet 42 p., 10 sheets, scale 1:24,000, http://pubs.usgs.gov/sim/3261/.

Keller, E.A., and Gurrola, L.D., 2000, Final report, July, 2000—Earthquake hazard of the Santa Barbara fold belt, California: NEHRP Award #99HQGR0081, SCEC Award #572726, 78 p., available at http://www.scec.org/research/98research/98gurrolakeller.pdf.

Keller, E.A., Duffy, M., Kennett, J.P., and Hill, T., 2007, Tectonic geomorphology and hydrocarbon potential of the Mid-Channel anticline, Santa Barbara Basin, California: Geomorphology, v. 89, p. 274–286.

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: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., 2007, California State University, Monterey Bay, Seafloor Mapping Lab Data Library: California State University, Monterey Bay, Seafloor Mapping Lab database, available at http://seafloor.csumb.edu/SFMLwebDATA.htm.

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., 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.

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/.

Mitchum, R.M., Jr., Vail, P.R., and Sangree, J.B., 1977, Seismic stratigraphy and global changes of sea level, part 6—Stratigraphic interpretation of seismic reflection patterns in depositional sequences, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: Tulsa, Okla., American Association of Petroleum Geologists, p. 117–133.

Murray, B., and Thieler, E.R., 2004, A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and “rippled scour depressions”: Continental Shelf Research, v. 24, no. 3, p. 295–315.

National Oceanic and Atmospheric Administration, 2011, Coastal ifSAR: Digital Coast, NOAA Coastal Services Center database, available 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/.

Phillips, E., 2007, Exploring rippled scour depressions offshore Huntington Beach, CA: Santa Cruz, University of California, M.S. thesis, 58 p.

Redin, T., 2005, Santa Barbara Channel structure and correlation sections—Correlation Section no. 34A, Summerland area, Santa Ynez Mountains, across the east central Santa Barbara Channel to the China Bay area, Santa Cruz Island: American Association of Petroleum Geologists, Pacific Section, Publication CS 34A, 1 sheet.

Redin, T., Kamerling, M., and Forman, J., 2005, Santa Barbara Channel structure and correlation sections—Correlation Section no. 35, North Ellwood–Coal Oil Point area across the Santa Barbara Channel to the north coast of Santa Cruz Island: American Association of Petroleum Geologists, Pacific Section, Publication CS 35, 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, available 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.

Suppe, J., Chou, G.T., and Hook, S.C., 1992, Rates of folding and faulting determined from growth strata, *in* McKlay, K.R., ed., Thrust tectonics: London, Chapman and Hall, p. 105–121.

Sylvester, A.G., 2001, Catalog of Santa Barbara earthquakes—1800 to 1960: University of California, Santa Barbara, database, available 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.

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 of London Special Publications, v. 146, p. 57–69.

Trembanis, A.C., and Hume, T.M., 2011, Sorted bedforms on the inner shelf off northeastern New Zealand—Spatiotemporal relationships and potential paleo-environmental implications: Geo-Marine Letters, v. 31, p. 203–214.

U.S. Geological Survey, 2009, National Archive of Marine Seismic Surveys: U.S. Geological Survey database, available 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.

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/.

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., 2009, Earth science in the urban ocean—The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 171–192.