

Seafloor terrain analysis and geomorphology of the greater Los Angeles Margin and San Pedro Basin, Southern California

Peter Dartnell*

U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA

James V. Gardner

University of New Hampshire, Durham, New Hampshire, USA

ABSTRACT

The seafloor off greater Los Angeles, California, has been extensively studied for the past century. Terrain analysis of recently compiled multibeam bathymetry reveals the detailed seafloor morphology along the Los Angeles Margin and San Pedro Basin. The terrain analysis uses the multibeam bathymetry to calculate two seafloor indices, a seafloor slope, and a Topographic Position Index. The derived grids along with depth are analyzed in a hierarchical, decision-tree classification to delineate six seafloor provinces—high-relief shelf, low-relief shelf, steep-basin slope, gentle-basin slope, gullies and canyons, and basins. Rock outcrops protrude in places above the generally smooth continental shelf. Gullies incise the steep-basin slopes, and some submarine canyons extend from the coastline to the basin floor. San Pedro Basin is separated from the Santa Monica Basin to the north by a ridge consisting of the Redondo Knoll and the Redondo Submarine Canyon delta. An 865-m-deep sill separates the two basins. Water depths of San Pedro Basin are ~100 m deeper than those in the San Diego Trough to the south, and three passes breach a ridge that separates the San Pedro Basin from the San Diego Trough. Information gained from this study can be used as base maps for such future studies as tectonic reconstructions, identifying sedimentary processes, tracking pollution transport, and defining benthic habitats.

INTRODUCTION

The seafloor off greater Los Angeles, in the regions known as the Los Angeles Margin and San Pedro Basin, has been extensively studied for the past century. This is a tectonically active region with offshore faults that recently have caused moderate earthquakes, including magnitudes 5.2 in 1979 and 5.0 in 1989,

both offshore the town of Malibu, and 6.3 in 1933, offshore Newport Beach (Fisher et al., 2004). The Palos Verdes Fault Zone strikes southeast across the San Pedro Shelf and has the potential to produce an earthquake as large as magnitude 7 (McNeilan et al., 1996), posing a hazard to onshore infrastructure and the lives of millions who live in the area. Large submarine landslides may have generated tsunamis that inundated the coastline (Bohannon

*pdartnell@usgs.gov

Dartnell, P., and Gardner, J.V., 2009, Seafloor terrain analysis and geomorphology of the greater Los Angeles Margin and San Pedro Basin, Southern California, 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. 9–28. doi: 10.1130/2009.2454(1.2). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

and Gardner, 2004; Locat et al., 2004), and the potential exists for future submarine landslides.

For decades, agencies at all levels of government, as well as academia, have studied the complex relationship between the coastal region and the ever-increasing population in Southern California. Most studies used the most detailed bathymetric maps of the day because understanding seafloor morphology is critical when modeling sediment processes, pollution transport, deciphering tectonics, and defining benthic habitats. Until the 1980s, studies, including the classic work by Emery (1960), relied on bathymetric maps generated from widely spaced, single-beam surveys. Although the seafloor was accurately mapped along the survey track lines, the bathymetry was unknown between survey lines, which means that most of the seafloor was poorly characterized. The advent of high-resolution, multibeam echosounders (MBES) in the past few decades has provided a new technique to efficiently map large areas of the seafloor at a meter spatial scale with centimeter-scale vertical resolutions (Hughes Clarke et al., 1996; Hughes Clarke, 2000a, 2000b). Because of their accuracy and high sounding densities, and their ability to efficiently cover 100% of the seafloor, MBES systems are presently in use by most of the world's hydrographic services, commercial marine surveyors, and navies, and in the scientific community.

The most recent studies of the Los Angeles Margin incorporate multibeam bathymetry data (Gardner and Mayer, 1998; Dartnell and Gardner, 1999; Gardner et al., 1999a; Marlow et al., 2000; Edwards et al., 2003; Gardner et al., 2003; Bohannon and Gardner, 2004; Fisher et al., 2004; Greene et al., 2004; Saucedo et al., 2009). Only a few studies of the inner-shelf regions have incorporated high-resolution bathymetry data (Kvitek et al., 2003; Dartnell and Gardner, 2004). This paper describes an empirical terrain analysis that identifies six physiographic provinces, as well as describes the fine-scale seafloor morphology of the Los Angeles Margin and San Pedro Basin from recently compiled, mostly publicly available MBES data collected by federal agencies and academia.

STUDY AREA

The study area encompasses ~4000 km², extending from the inner continental shelf to the deepwater San Pedro Basin off the greater Los Angeles region of Southern California (Fig. 1). The area measures ~140 km NW-SE by ~35 km NE-SW and ranges in water depth from 5 m to >900 m. The region is bounded by Point Dume on the northwest, Dana Point on the southeast, and the Catalina Island platform on the west. This is the eastern segment of the Southern California Continental Borderland (Shepard and Emery, 1941; Emery, 1960), which is composed of an extensive series of ridges and basins between the mainland and the Patton Escarpment. The geologic setting of this region has been described in detail by Shepard and Emery (1941), Emery (1960), ten Brink et al. (2000), and Fisher et al. (2004), to name a few. The present-day seafloor morphology has been shaped by a complex interaction of tectonic forces, volcanism, climate fluctuations, and sedimentary processes.

Prior to the Miocene, the Farallon Plate was subducted under the North American Plate in the vicinity of Southern California. In the early Miocene, part of the Farallon Plate located west of Southern California began to move northward with the Pacific Plate (Nicholson, et al., 1994) and replaced compressional forces from margin-normal subduction with extensional forces from oblique rifting and strike-slip deformation. Volcanism followed the crustal extension (Wright, 1991; Dickinson, 1997; Bjorklund et al., 2002) resulting in local uplifts and exposed pillow basalts. In the late Pliocene through the Quaternary, the continental margin was deformed by simultaneous strike-slip faulting and compression (Atwater, 1970; Wright, 1991; Crouch and Suppe, 1993; Bohannon and Geist, 1998). The result of the interaction of tectonic and volcanic forces formed a series of NW-SE-trending ridges and basins. Quaternary climatic fluctuations produced eustatic changes of sea level that periodically lowered local sea level more than 100 m, allowing rivers, including the Los Angeles, San Gabriel, and Santa Ana Rivers, to flow across the exposed continental shelf to the shelf edge. Turbidity currents flowed off the margin following submarine canyons and built submarine deltas across the floor of the San Pedro Basin and San Diego Trough. Sedimentary processes have cut numerous gullies into the basin slopes, and local failures have generated debris flows that deposited sediment along the proximal basin floor.

DATA SETS

Mostly publicly available, multibeam data sets collected and processed by federal agencies or academia are used in this study. Most of the data sets were collected for research purposes, and they have been rigorously processed and tide corrected. During three separate surveys, the continental shelf, slope, and the eastern portions of the San Pedro Basin from Point Dume to Dana Point were mapped by the U.S. Geological Survey (USGS) (Gardner and Mayer, 1998; Gardner et al., 1999a, 1999b, 2002). The near-shore regions in northern Santa Monica Bay and around the Palos Verdes Peninsula were mapped by California State University–Monterey Bay (Kvitek et al., 2003). The region near Catalina Island and the western portion of San Pedro Basin were mapped by the National Oceanic and Atmospheric Administration (NOAA) (C.G. Fox, 2000, personal commun.). The San Pedro Basin regional bathymetry was mapped by the Scripps Institution of Oceanography (SIO). See Appendix A for the details of the MBES systems used during each survey and the data availability. Details of high-resolution, multibeam echosounders can be found in Hughes Clarke et al. (1996).

The spatial resolution of MBES data is a function of water depth, the multibeam frequency, and the sonar beam angle. MBES data sets from the study area vary in resolution because different MBES systems were used that had frequencies ranging from 12 kHz to 300 kHz in water depths from shallower than 5 m to deeper than 900 m. The near-shore bathymetric data collected by California State University–Monterey Bay are available

at 2-m pixel resolution; the USGS data are available at 4-, 8-, and 16-m pixel resolutions; while the NOAA and SIO data were processed to 20-m pixel resolution. For the terrain analysis, the bathymetry data from the continental shelf in water depths shallower than 100 m were merged at 8-m resolution, whereas the data collected from water depths deeper than 100 m were merged at 20-m resolution.

TERRAIN ANALYSIS

Often, physiographic classifications or segments of the seafloor are generated by manually outlining major geologic features on base maps. This approach is time consuming and subjective, often resulting in different interpretations between interpreters and inconsistent interpretations between study

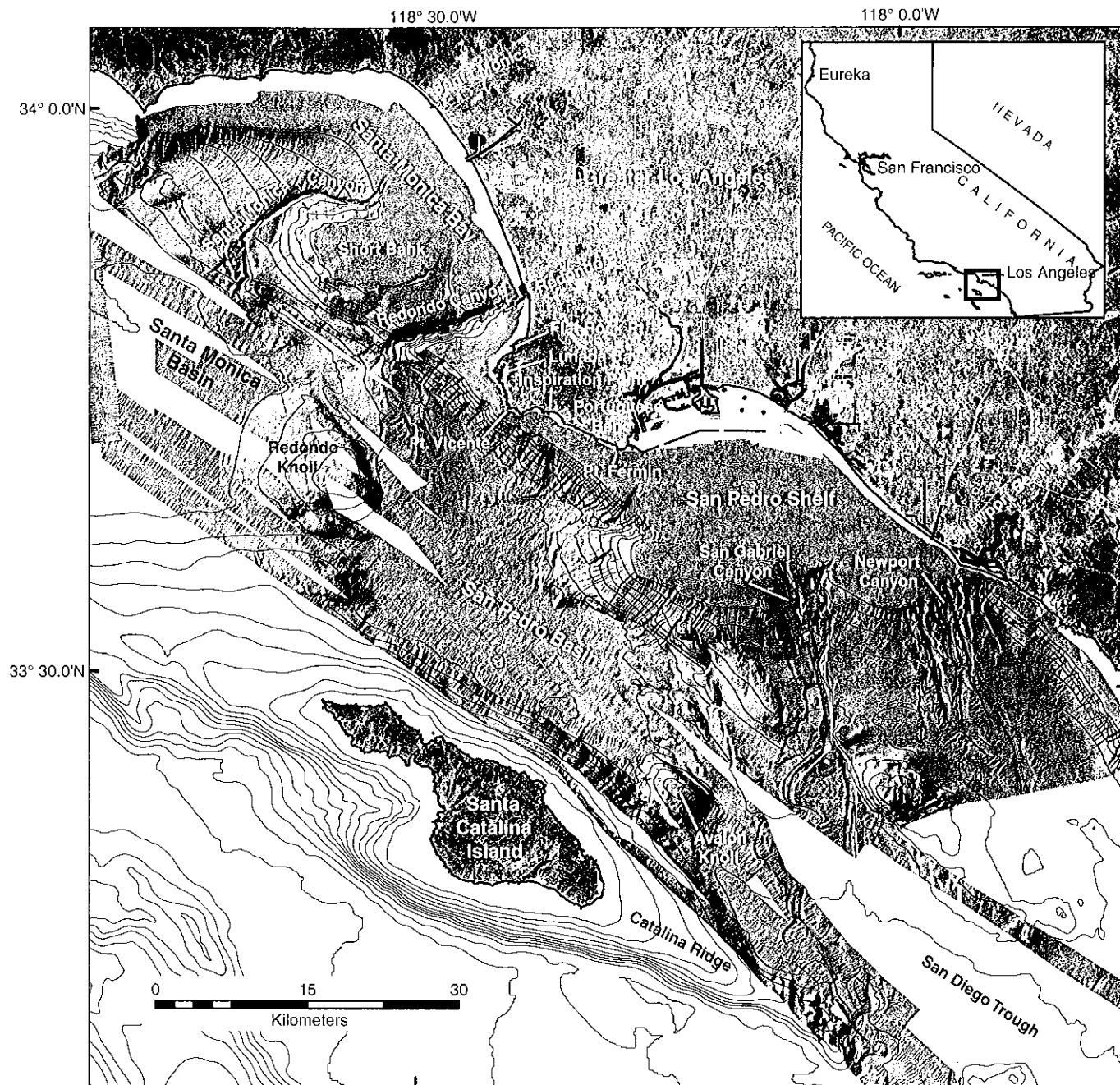


Figure 1. The seafloor offshore the greater Los Angeles area. The study area includes the continental shelf and basin slope from Dume Point south to Dana Point and offshore to Catalina Island including the San Pedro Basin and the northern end of the San Diego Trough. Water depths within the study area range from <5 m to >900 m in San Pedro Basin. Land displayed using grayscale Landsat-7 imagery. North is toward the top of the image.

areas. Although this approach is useful when considering small areas of the seafloor (perhaps tens of km²) resulting in uniform physiographic segments, the approach yields unpredictable results and is unwieldy, if used for large regions of the seafloor (hundreds of km²).

Similar to the work of Iampietro et al. (2005) and Wright et al. (2005), an empirical approach is employed here that incorporates geographic information system (GIS) and remote-sensing analytical techniques to classify digital MBES bathymetry pixel-by-pixel into seafloor physiographic provinces. This approach can identify small- and large-scale features and can aid in more extensive seafloor geologic and benthic-habitat characterizations. The approach calculates two indices of seafloor morphology—seafloor slope (S) and Topographic Position Index (TPI)—and uses the indices in a hierarchical, decision-tree classification process to delineate seafloor provinces. Seafloor slope measures the maximum change in depth between adjacent pixels and is calculated using standard GIS techniques. The resolution of the derived slope grid is dependent on the resolution of the original MBES bathymetry. For the present study, a high-resolution slope grid was generated for the shelf region (HRslope), and a lower resolution slope grid was generated for the basin slope and basin region (LRslope).

TPI, also known as Bathymetric Position Index (BPI) for seafloor analysis, is a measure of the location of a given depth point to the surrounding depth points (Iampietro et al., 2005). The TPI, for example, identifies concave shapes such as rock outcrops, pinnacles, and reefs, and convex shapes such as canyons, gullies, and pits. The TPI values are generated using the MBES bathymetry and GIS map algebra according to a modified formula of Weiss (2001):

$$TPI_{\text{scalefactor}} = (\text{bathy} - \text{focalmean}(\text{bathy}, \text{annulus}, \text{irad}, \text{orad}) + 0.5),$$

where:

scalefactor = outer radius in map units;

bathy = bathymetry grid;

focalmean = ESRI GRID function that finds the mean of the values within a specified neighborhood and sends it to the corresponding pixel location on the output grid;

annulus = the processing neighborhood comprised of one smaller circle within a larger circle (donut shape);

irad = inner radius of annulus in pixels; and

orad = outer radius or annulus in pixels.

Positive TPI values represent concave surfaces, whereas negative TPI values represent convex surfaces. The TPI is entirely scale dependent, but it can identify different sizes of features by adjusting the outer radius and inner radius. Various radii from 3 to 100 pixels were tested, and an outer radius of 7 pixels (*TPI7*) was chosen for the shelf region because this radius captures the fine-scale detail resolved by the high-resolution MBES data. An outer radius of 9 pixels (*TPI9*) was chosen for the basin slope and basin region because this radius captures the large-scale features from the lower resolution MBES data. The two indices (S and TPI), along with depth information, were then used in a hierar-

chical, decision-tree classification (Dartnell and Gardner, 2004) to delineate seafloor provinces.

To test if the terrain analysis is consistent from one region to another, an analysis to identify physiographic provinces was first tested on a subarea of the overall study area that extends from Point Dume, south to the Palos Verdes Peninsula, and west to ~900 m water depth. This Santa Monica Bay subarea is similar in extent to that described by Gardner et al. (2003). The S and TPI parameters that generated the best results on the subarea were then applied to the entire study area multibeam data set to see if they correctly identified the physiographic provinces of this larger area. These results were compared to previous manual interpretations of a similar extent by Greene et al. (2004).

The TPI and slope grids together with depth were analyzed using a hierarchical, decision-tree classification that is part of the ERDAS Imagine 8.7 software package (ERDAS, 1999). The classification is a rules-based approach that uses a hierarchy of conditions to parse the input data into a set of classes. The decision-tree framework was developed from empirically determined textural rules, variables, and hypotheses. A hypothesis is defined as an output class, such as gullies and canyons; a variable is a raster grid (i.e., *TPI9*); and a rule is a conditional statement about the variable's pixel (data) values that describe the hypothesis. Because the index grids are co-registered to one another, rules can be established that relate pixel values within or between images that will ultimately classify a new seafloor province. For example, if a pixel within the slope grid has a value greater than 3, the same pixel in the *TPI9* grid has a value greater than -20, and the pixel in the depth grid has a value between 100 m and 700 m, then the pixel at that location in the new province grid will be assigned to a steep-basin slope class. Multiple rules and hypotheses can be linked together into a hierarchy that describes the hypothesis. The classified province grid was tested and refined by overlaying the grid with shaded-relief bathymetry.

For the Santa Monica Bay subarea, six provinces were identified: (1) high-relief shelf, (2) low-relief shelf, (3) gentle-basin slope, (4) steep-basin slope, (5) gullies and submarine canyons, and (6) basins. A high-relief shelf includes regions of the seafloor that are shallower than 80 m (Table 1), have *HRslope* values $\geq 2^\circ$, and have a *TPI7* ≥ 0.8 . A low-relief shelf includes regions shallower than 100 m, *HRslope* $< 5^\circ$, and a *TPI7* < 0.9 . Gentle-basin slope regions are between 100- and 700-m water depth, have *LRslope* values $< 5^\circ$, and have a *TPI9* > -20 . Steep-basin slope regions are between 100- and 700-m water depths, have *LRslope* values $\geq 3^\circ$, and a *TPI9* ≥ -20 . Gullies and canyons are shallower than 800-m water depth, have *LRslope* values $> 2^\circ$, and have a *TPI9* < -1 . Finally, basins have water depths deeper than 700 m, have *LRslope* values $\leq 30^\circ$, and have a *TPI9* > -30 .

Although the results of the hierarchical, decision-tree classification delineated physiographic provinces similar to those identified by Gardner et al. (2003) (Fig. 2), the empirical approach identified finer scale seafloor features. Both approaches identified the shelf, basin slope, apron (here called gentle-basin slope), submarine canyons, and basin with only slight differences in

TABLE 1. CLASSIFICATION RESULTS DEFINING SEAFLOOR PROVINCES AND AERIAL COVERAGE OF EACH PROVINCE

Province	Slope (°)	Topographic Position Index	Depth (m)	Approximate area (km ²)
High-resolution shelf	High-resolution slope ≥ 2	TPI7 ≥ 0.8	0–80	15
Low-resolution shelf	High-resolution slope < 50	TPI7 < 0.9	0–100	803
Gentle-basin slope	Low-resolution slope < 5	TPI9 > -20	100–700	707
Steep-basin slope	Low-resolution slope ≥ 3	TPI9 ≥ -20	100–700	741
Gullies and canyons	Low-resolution slope > 2	TPI9 < -1	≤ 800	215
Basin	Low-resolution slope ≤ 30	TPI9 > -30	> 700	1528

boundaries. However, the empirical approach identified individual rocky outcrops exposed on the continental shelf (Dartnell and Gardner, 2004), as well as gullies incised into the basin slope. Gardner et al. (2003) identified a shelf-projection region (Short Bank) as a marginal plateau; however, because this feature is unique to Santa Monica Bay, this area is included in the more general high-relief and low-relief shelf.

Using seafloor slope, TPI, or depth by themselves did not correctly identify all of the seafloor provinces outlined by using the combination of the three indices. Although slope alone can identify the shelf, steep-basin slope, and gentle-basin slope, this criterion alone does not discriminate gullies and canyons because these features have slopes with similar values as the steep- and gentle-basin slopes. Similarly, TPI identified rocky outcrops, gullies, and canyons; however, it did not separate steep-basin slope from gentle-basin slope. Only the combination of the indices in the hierarchical decision-tree correctly identified all the provinces.

As with the Santa Monica Bay subarea, for the full Los Angeles Margin and San Pedro Bay bathymetry data set, seafloor slope and TPI were calculated from the high-resolution shelf bathymetry (*HRslope*, *TPI7*) and the low-resolution basin slope and basin bathymetry (*LRslope*, *TPI9*). The indices together with depth were analyzed using the hierarchical, decision-tree classification method using the rules developed from the Santa Monica Bay subarea.

The results of the decision-tree classification (Figs. 3A and 3B) identified and separated both the fine-scale morphology on the shelf and the larger scale features in deeper water. Rock outcrops exposed in the Horseshoe Kelp area, on the outer San Pedro Shelf were correctly identified as high relief even though the outcrops have relief of less than 3 m. Gullies cut into the steep basin slope were identified from offshore the Palos Verdes Peninsula, south of the San Pedro Sea Valley, south of Newport Beach, as well as northeast of Catalina Island. The numerous channels of the San Gabriel and Newport submarine canyons were identified and traced from the coast, down the steeper basin slope, and to the basins.

The results from the empirical classification match well with manual interpretations of Greene et al. (2004) (Fig. 3C). Gullies with widths less than 60 m and outlined by the manual interpretation are delineated by the empirical classification. Also, outcrops with 1–3 m of relief at the shelf edge south of the San Pedro Sea Valley are delineated with greater detail than the manual inter-

pretation. While this empirical process cannot identify all of the provinces identified by Greene et al. (2004), such as landslide in gully or rockfall in canyon, the process can delineate the more general provinces and can aid in further manual interpretations, especially of small-scale features.

There are misclassified pixels within the map. Portions of the shelf region are identified as high-relief shelf, whereas the pixels should be identified as low-relief shelf. The linear pattern of these high-relief pixels shows that the misclassification is probably due to artifacts within the MBES data sets. Also, depressions within both the steep-basin and gentle-basin slopes are incorrectly identified as gullies and canyons. These areas have slope, TPI, and depth characteristics similar to the gullies and canyons and cannot be separated using this terrain analysis. Similarly, both the Redondo Knoll and Avalon Knoll are identified as steep-basin slope and gentle-basin slope. Whereas technically these knolls are not basin slopes, their terrain is identical to basin-slope regions.

DISCUSSION

High-Relief Shelf

The results of the terrain analysis subdivided the physiography of the Los Angeles Margin and San Pedro Basin into six provinces—high-relief shelf, low-relief shelf, gentle-basin slope, steep-basin slope, gullies and canyons, and basin. The major high-relief shelf regions (15 km²) are found in central Santa Monica Bay, directly offshore Palos Verdes Peninsula, and on the western San Pedro Shelf, although other smaller pockets are found throughout the shelf areas. The high relief in central Santa Monica Bay (Short Bank) varies from less than a meter to more than 14 m. This region is composed of rock outcrops with pockets of gravelly, muddy sand and muddy sand and NW-SE-trending linear ridges composed of rock boulders (Dartnell and Gardner, 2004).

The high-relief shelf off the Palos Verdes Peninsula ranges from less than a meter to more than 17 m. Greene et al. (2004) identify this high relief as differentially eroded, deformed bedrock, deformed hummocky bedrock, hummocky sediment-covered, deformed bedrock, as well as volcanic rock.

The high relief at the western edge of the San Pedro Shelf (Horseshoe Kelp) has less relief than both central Santa Monica

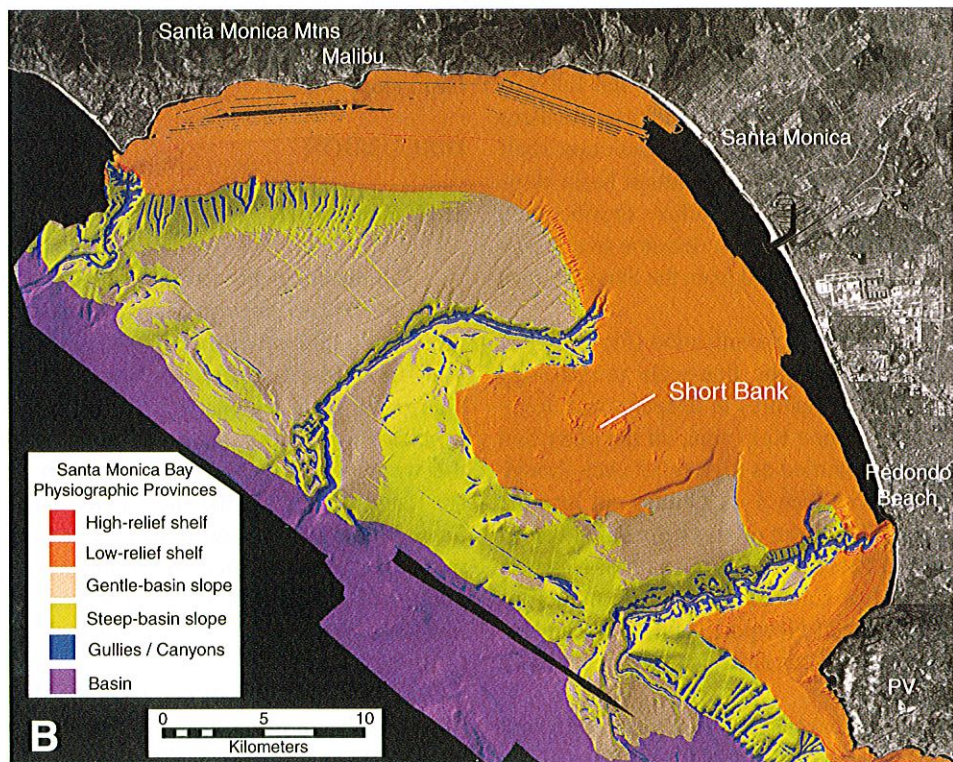
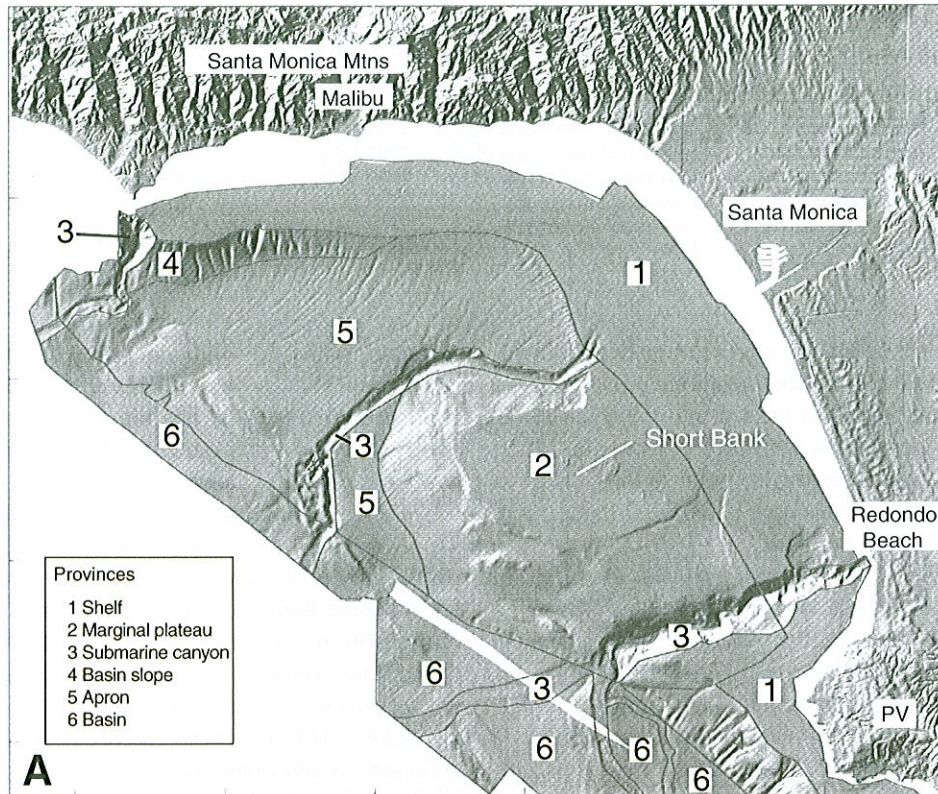


Figure 2. (A) Comparison between seafloor provinces within Santa Monica Bay defined by Gardner et al. (2003) and (B) the terrain analysis using seafloor slope, Topographic Position Index, and depth. Land displayed using shaded-relief topography in (A) and grayscale Landsat-7 imagery in (B). North is toward the top of the images.

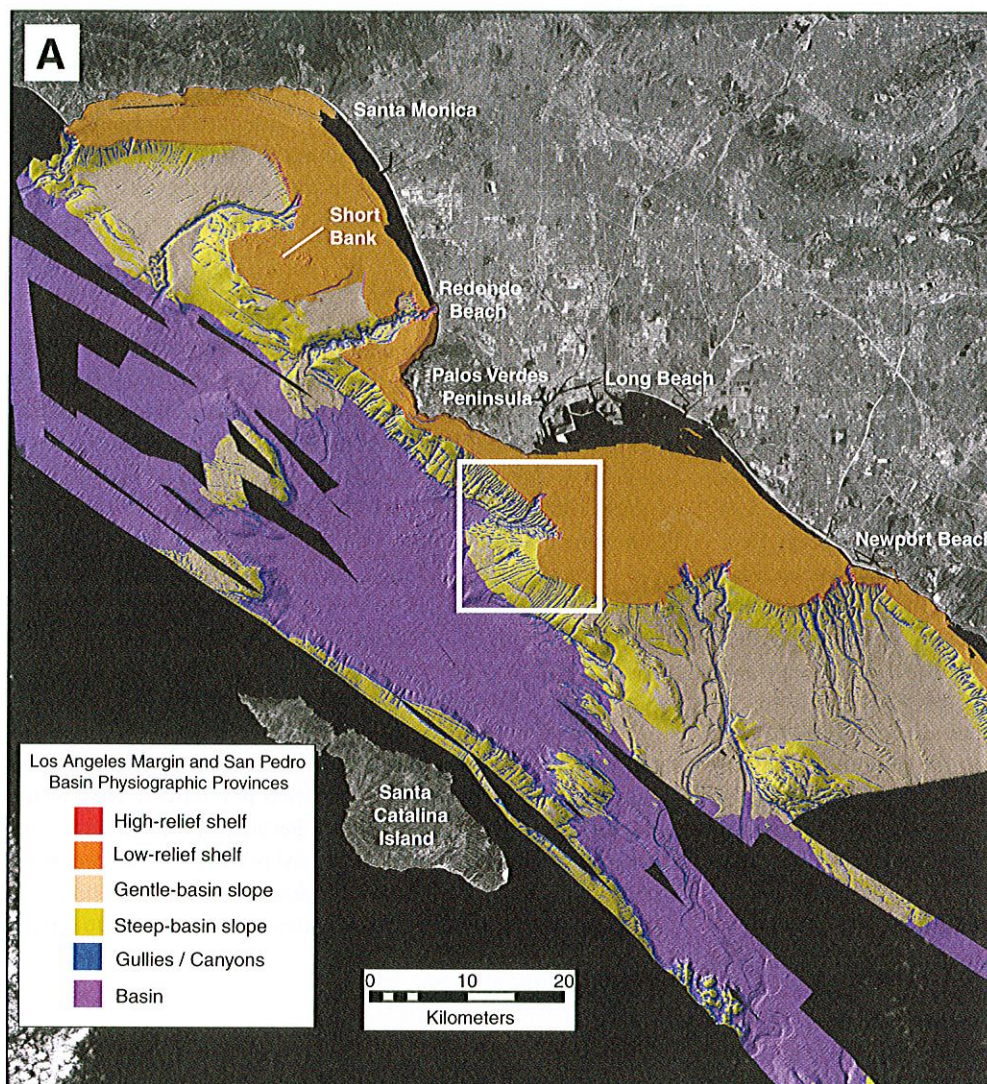
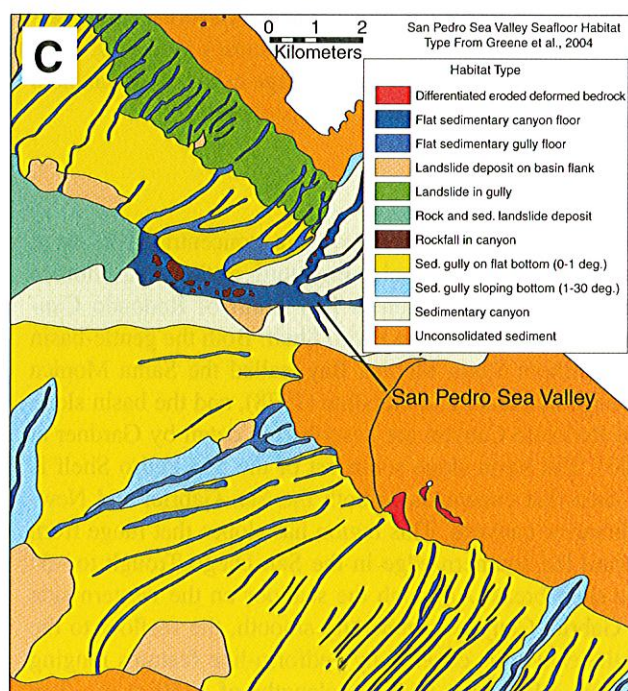
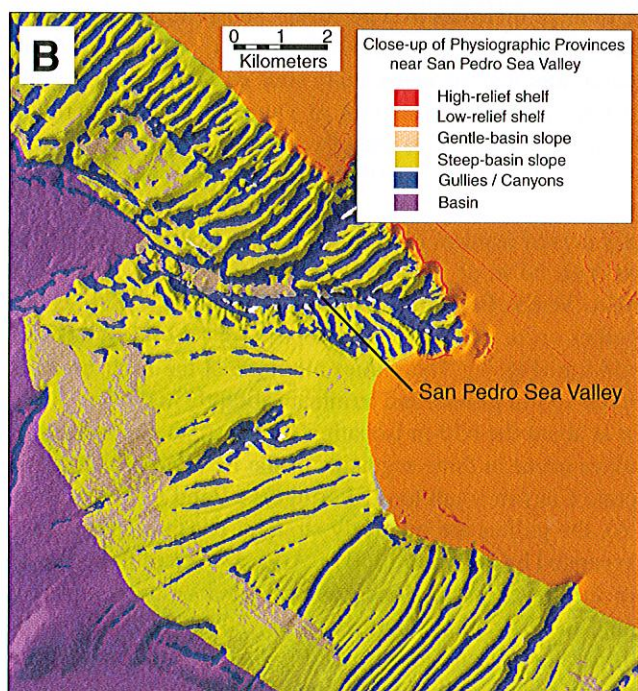


Figure 3. The result of the terrain analysis over the entire study area (A) defining six seafloor provinces: (1) high-relief shelf, (2) low-relief shelf, (3) gentle-basin slope, (4) steep-basin slope, (5) gullies and canyons, and (6) basins. Land displayed using grayscale Landsat-7 imagery. (B) Close-up view of the provinces near the San Pedro Sea Valley. (C) Seafloor geology identified manually by Greene et al. (2004) over the same extent as (B). North is toward the top of the images.



Bay and Palos Verdes Peninsula (Fig. 4). Both northwest-southeast- and northeast-southwest-trending ridges are identified in this region. The ridges that typically have widths less than 40 m and are less than 3 m high are correctly identified based on the shaded-relief bathymetry as well as georectified seafloor photographs that show the ridges are composed of rock outcrop, while the smooth shelf is composed of coarse sand and shell hash. This area has been folded and uplifted by movement on the Palos Verdes Fault to the east.

Low-Relief Shelf

The majority of the shelf region has low relief and is covered with muds and sands (Leecaster, 2003; Sommerfield and Lee, 2003). The sands are mainly concentrated in the high-energy, near-shore regions, as well as around the high-relief regions on Short Bank in central Santa Monica Bay (Dartnell and Gardner, 2004) and the Horseshoe Kelp region on the western San Pedro Shelf.

A few slumps have occurred on the inner shelf, seen as a set of lobes that trend offshore in 45 m of water, northwest of Marina del Rey (A on Fig. 5). The lobes are 800–1000 m long with ~1 m of relief. Another slump was found inshore of Short Bank in ~40 m water depth (B on Fig. 5). This slump has an 1800-m-long scour behind it, and the deposit has a volume of ~2100 m³. Both of the landslides occurred on the seafloor with much less than 1° of slope.

The high-relief shelf and low-relief shelf provinces are separated in the terrain analysis because of their different geomorphic characteristics. The mainly rocky terrain of the high-relief shelf created by tectonic uplifting creates higher values of seafloor slope and TPI than the low-relief shelf mainly influenced by hemipelagic sedimentation and across-shelf sedimentary processes. These shelf provinces need to be separated because each has drastically different seafloor habitats and sedimentary processes. Once the provinces are identified, aerial coverage calculations can help identify benthic-species densities and distributions.

Gentle-Basin Slope

Gentle-basin slopes (707 km²) are concentrated in three regions—northern Santa Monica Bay north of the Santa Monica Canyon, southern Santa Monica Bay north of Redondo Canyon, and southeast of the San Pedro Shelf. Both the gentle-basin slope in northern Santa Monica Bay, called the Santa Monica slope wedge by Haner and Gorsline (1978), and the basin slope north of Redondo Canyon are described in detail by Gardner et al. (2003). The basin slope southeast of the San Pedro Shelf is a large area that encompasses both the San Gabriel and Newport submarine canyons. This region has slopes that range from <1° toward the southern edge in the San Diego Trough to ~5° near the shelf break. Although the seafloor on the western side of San Gabriel Canyon is generally smooth, the seafloor to the east of the canyon is covered by bedform-like features ranging in size from <1 m high with wavelengths of ~150 m to ~2 m

high with wavelengths over 200 m. The smooth slope to the west of the canyon suggests this region is influenced by hemipelagic sedimentation, whereas the bedforms to the east of the canyon suggest this region is the locus of downslope processes that are channeled by gullies just below the shelf break.

Steep-Basin Slopes

Steep-basin slopes are defined as slopes greater than 3° that separate the shallow shelf provinces from the deeper basins. Almost all steep-basin slopes have relatively straight gullies that originate at the shelf break and terminate at the base of the slope (see below). The exception to this is the steep-basin slope just west of Short Bank in central Santa Monica Bay (Fig. 3). The steep-basin slope in this area has similar characteristics to all the other steep-basin slopes in the study area (>3° slopes, slightly convex to concave profile), although no gullies are seen in the bathymetric data. This suggests that the Short Bank Region is sediment starved and little sediment flows off the bank to create linear erosional gullies such as are seen on the other steep-basin slopes.

Gentle-basin slope and steep-basin slope provinces are separated in the terrain analysis mainly through their relative slope steepness. Although separating the two is relatively easy in the analysis, the separation is important because of the different sedimentary processes and offshore hazard potential of the two provinces. For example, the steep-basin slopes have a greater potential for failure, which could potentially cause destructive tsunamis.

Gullies and Canyons

Gullies

Gullies and canyons identified by the terrain analysis are small to large incisions into the steep- and gentle-basin slopes. Gullies occur on the steeper basin slopes (3° to 25°) and are located in four regions in the study area, each with unique gully characteristics. The gullies east of Dume Canyon in northern Santa Monica Bay incise into the steep-basin slope (8°–23°) and become less distinct farther to the east as the basin slope decreases. The gullies typically occur as single, straight to slightly curved features that range in width from 60 m to 300 m across with 60 m of vertical relief (Gardner et al. 2003). Off the Palos Verdes Peninsula and south of San Pedro Sea Valley, the gullies occur on steep-basin slopes (10° to 25°) and extend for ~38 km (Fig. 6). The gullies all begin at the shelf break at about the 100-m isobath and terminate abruptly in the San Pedro Basin at about the 650-m isobath. Three distinct characteristics of gullies occur in three segments of the basin slope. From the Redondo Canyon south to off Portuguese Bend (segment A on Fig. 6), the gullies are relatively straight, but unevenly spaced and separated by 300 m to 1700 m. Also, a series of failure scars where the lower basin slope has collapsed or been undercut is found in this region (Gardner et al., 2003). A sharp transition separates the unevenly spaced gullies of segment A from the closely spaced gullies of segment B (Fig. 6). The change in

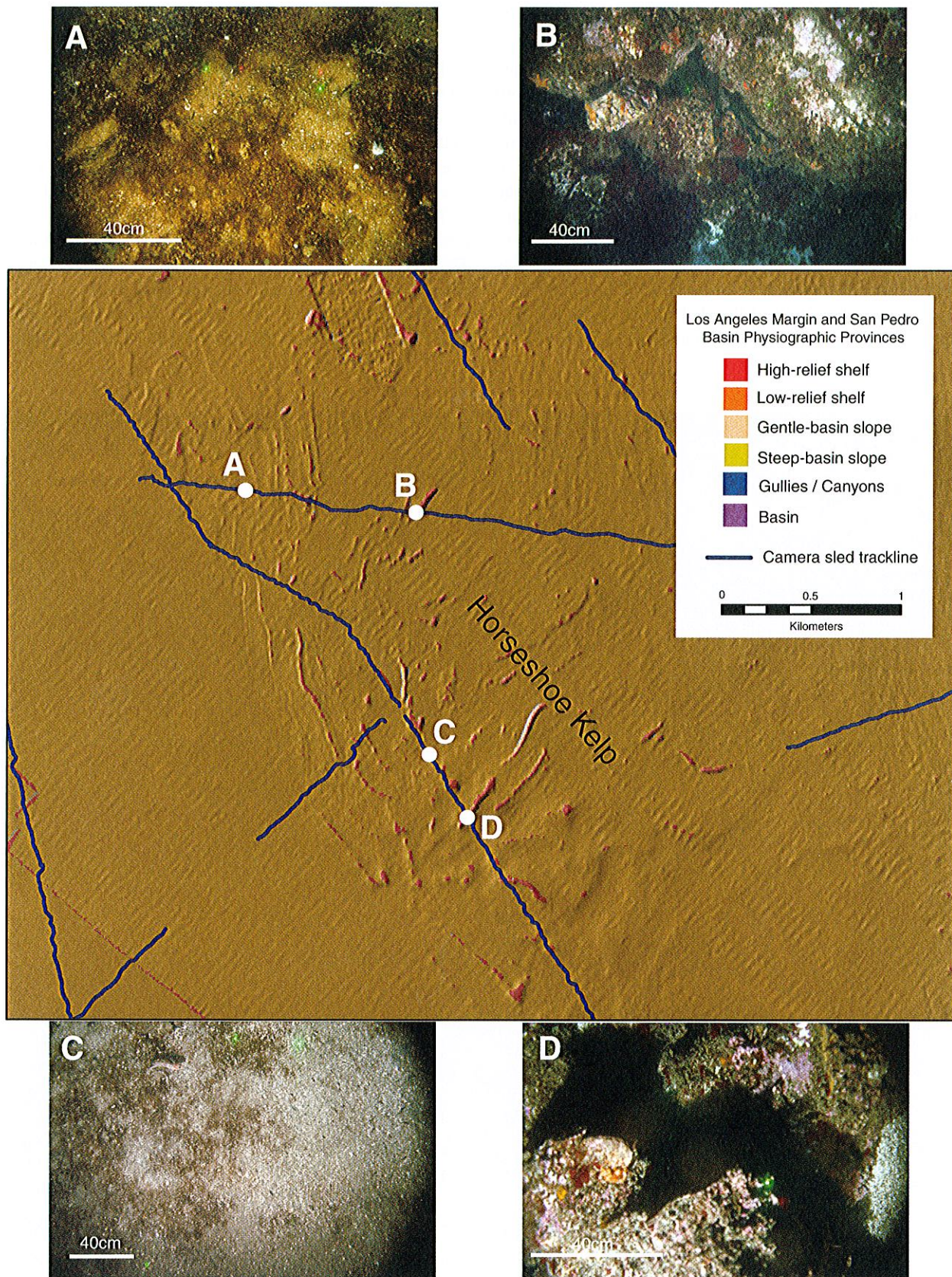


Figure 4. Close-up view of the seafloor provinces draped over shaded-relief bathymetry of the Horseshoe Kelp region on the western San Pedro Shelf. See Figure 12 for the location. Georectified seafloor photographs collected in December 2004 show that the high-relief shelf is composed of rock outcrop (photos B and D), while the low-relief shelf is composed of sands and shell hash (photos A and C).

gully style occurs at the location of a relatively recent submarine landslide (Lee et al., 2003; Bohannon and Gardner, 2004) south of Portuguese Bend. This entire region of densely spaced gullies has been identified as a large submarine failure (Emery and Terry, 1956; Hampton et al., 2002; Lee et al., 2003; Normark et al., 2004). Gullies separated by 200–350 m are found from the landslide south to the head of the San Pedro Sea Valley. The gullies increase in incision depth from 10 m to 40 m in the north to 40–80 m near the head of the San Pedro Sea Valley (Fig. 6). The shelf break along this segment is more rounded than along segment A, and the water depth of the shelf break decreases from 100 m at the northwestern end of the landslide to 70 m at head

of the sea valley. One large gully incises into the slope by almost 2 km toward the southern third of segment B.

A different style of gully is found south of the San Pedro Sea Valley (segment C on Fig. 6). These gullies are typically long, straight, and narrow. The gullies are separated by only 100 m in some areas, whereas in other areas they are separated by as much as 700 m. The larger gullies toward the south end of segment C have runout channels that trend onto the floor of San Pedro Basin. The southernmost gully in segment C (labeled E on Fig. 6) has been diverted around the SE end of a local uplift.

The gullies south of Newport Beach occur along the entire mapped extent of the steep-basin slope from south of the

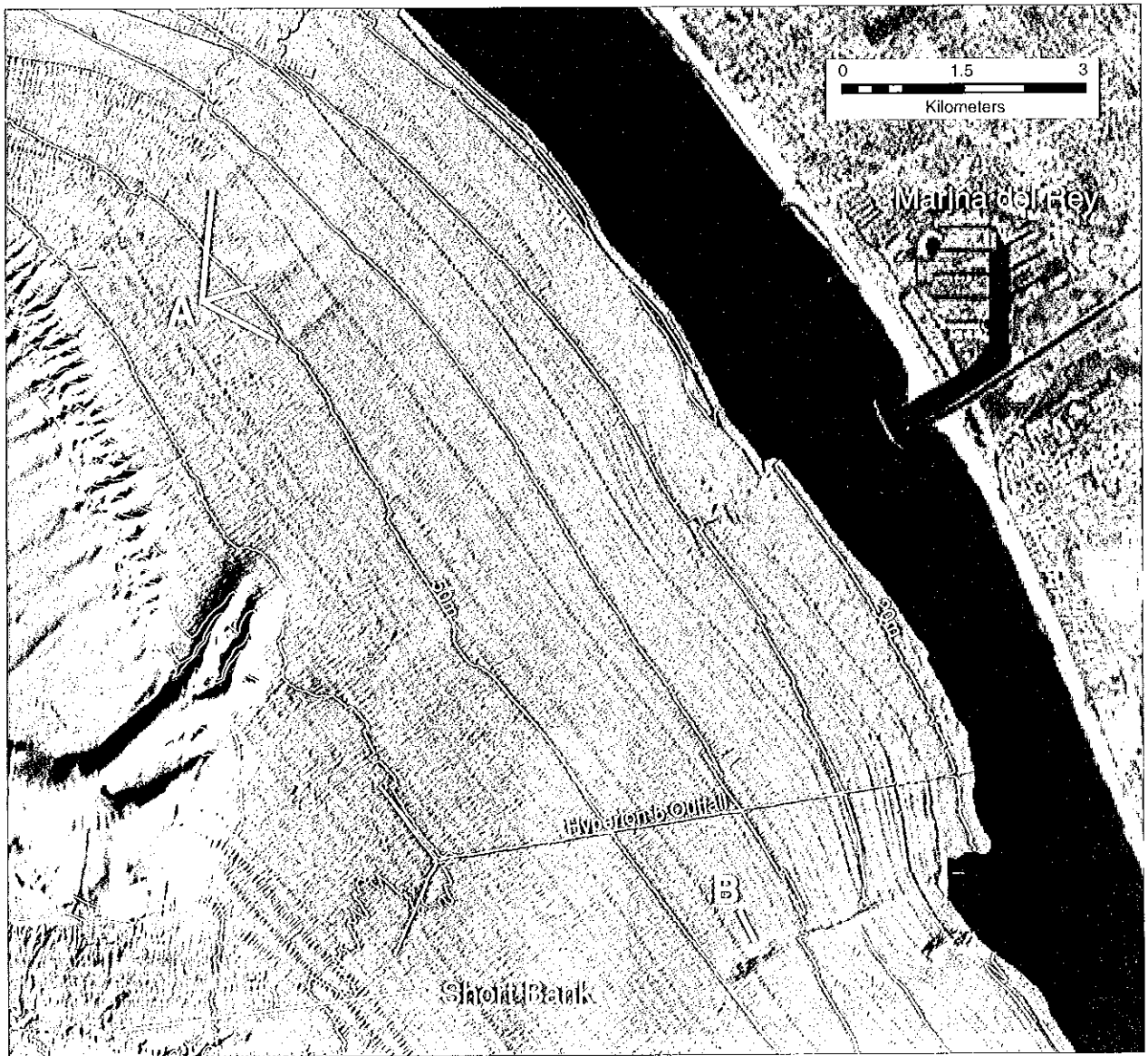


Figure 5. The inner continental shelf within Santa Monica Bay, offshore Marina del Rey. See Figure 12 for the view location. A series of lobes (A) and a scour channel (B) show the location of mass-movement events. Land displayed using grayscale Landsat-7 imagery. North is toward the top of the image.

Newport Canyon to the southern end of the study area. The gully spacing decreases from a range of 425 m to 1500 m near Newport Canyon to only 300–400 m toward the southern extent of the mapped area. Gullies are also found at the base of the Santa Catalina Island basin slope. These gullies are fairly linear in plan and abruptly terminate at the base of the basin slope.

All of the gullies within the study region are presumably caused by downslope erosional processes, as sediment is transported from the mainland shelf down into the offshore basins. Identifying the gullies can help in source-to-sink studies, such as determining pathways along which contaminants can travel from urbanized rivers to the deep basins.

Canyons

Dume, Santa Monica, and Redondo Canyons are described in detail by Gardner et al. (2003); therefore, they are not discussed here. San Gabriel Canyon begins ~15.5 km from the present-day mouth of the San Gabriel River, its ancestral source. Seismic profiles that cross the San Pedro Shelf reveal paleochannels that connect the San Gabriel River to the heads of the San Gabriel Canyon system (Wolf and Gutmacher, 2004). The head of the canyon is composed of an east and west branch, forming what is called here the San Gabriel Canyon system. Both the east and west branches have multiple heads that incise more than a kilometer into the outer edge of the San Pedro Shelf. The head



Figure 6. Multibeam echosounder–shaded bathymetry of the outer continental shelf, basin slope, and San Pedro Basin. Segments A–C show regions with different patterns of gullies incised into the steep-basin slope. Segment E shows the location of the southern limit of sediment supply from the continental shelf into the San Pedro Basin. Land displayed using grayscale Landsat-7 imagery. North is toward the top of the image.

of the western branch is composed of two shelf-edge incisions ("A" on Fig. 7A), each ~1.5 km long that begin in water depths of ~50 m. The sculpted nature of the west branch canyon walls suggests the canyon channel has meandered laterally over distances approaching 900 m and is entrenched ~80 m into the slope. The thalwegs of both incisions of the western branch descend with slopes of 3° to 4° over their lengths.

The eastern branch of the San Gabriel Canyon system begins in ~35 m water depths and meanders downslope for ~9 km. Slumps and terraces occur along both sides of the canyon walls ("S" and "T," respectively, on Fig. 7A). The east branch channel captures the west branch channel ~8.5 km downslope, leaving the west branch channel hanging 15 m above the east branch channel ("C" on Fig. 7A). The main channel then progresses downslope for 9.5 km with a fairly uniform ~600 m width and an incision depth of ~60 m. Then, at the northern end of Lasuen Knoll (Figs. 7B and 8), the main San Gabriel channel has abandoned a former channel that now resides ~15 m above the main channel. Landslide scars on the northern wall of the abandoned channel, together with the hummocky nature of the adjacent channel floor, suggest that the channel abandonment was caused by landslides that blocked the former channel. The main channel continues to the southwest away from Lasuen Knoll through a series of broad meanders as it crosses the San Diego Trough (Fig. 8) and eventually passes south of Catalina Ridge and into the Catalina Basin (Fig. 8). The channel has at least two levels of terraces above the channel floor in the immediate vicinity of the Catalina Ridge, and the thalweg has incised as much as 70 m into the basin sediments ("B" on Fig. 8).

Newport Canyon is another canyon-channel complex composed of at least 13 individual canyon-channel systems. The head of the entire canyon-channel complex is located along the southern end of the San Pedro Shelf, ~3.5 km from the present-day mouth of the Santa Ana River, its ancestral source, in the area where the shelf narrows from greater than 6.5 km to less than a kilometer. The upper canyon part of the complex is composed of seven large channels ("A" through "G" on Fig. 9) together with a number of smaller and abandoned channels spread over a distance of 10 km along the shelf break. The easternmost channel ("A" on Fig. 9) heads in an upper basin-slope amphitheater that spans a distance of 1.9 km. The easternmost subchannel within the amphitheater is the dominant one, and it captures each of the other canyon channels within the amphitheater. Downslope of the last capture, the single canyon channel can be traced 5 km beyond the base of the slope and onto the basin floor where its

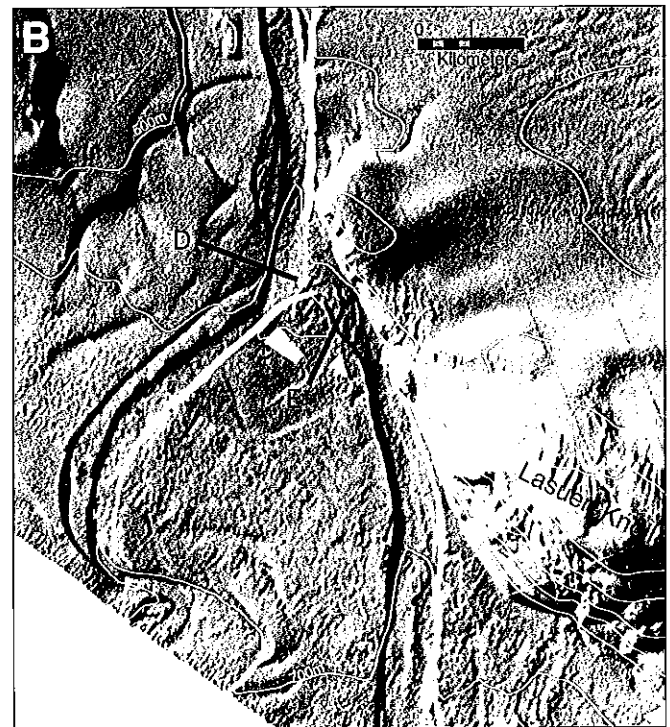
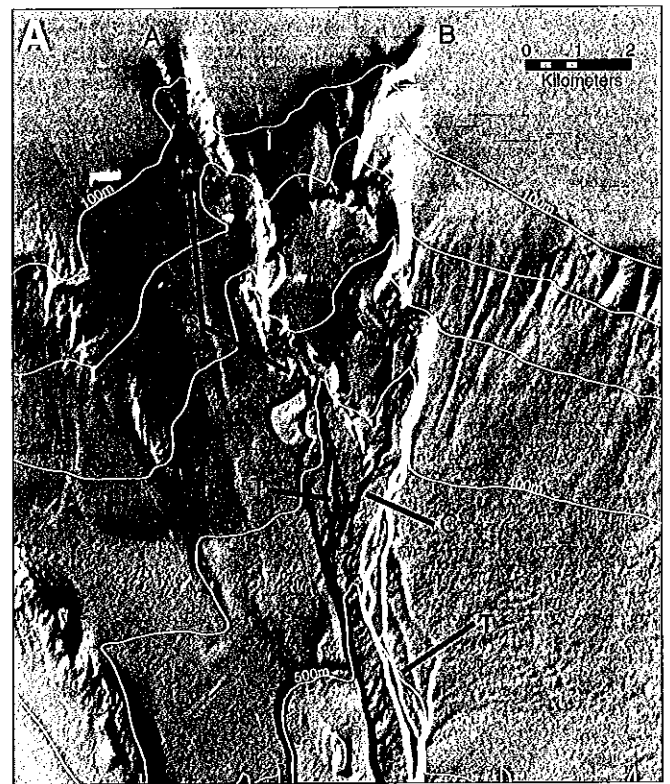


Figure 7. Map views of the shaded bathymetry of the upper reaches of San Gabriel Canyon. See Figure 12 for the view locations. (A) Segments A and B show the two branches at the head of the canyon. Segment C shows where channel B has undercut channel A. Segments S and T show the locations of slumps and terraces, respectively. (B) The portion of the San Gabriel Canyon where it splits into two channels north of the Lasuen Knoll. Segment D shows where the active channel has undercut the eastern channel that may have been blocked by a landslide (segment E). North is toward the top of the image.

course has been diverted by massive sediment failures shed off the basin slope.

Canyon-channel B ("B" on Fig. 9), the next system to the west, is similar in shape to canyon-channel system A but has fewer well-defined canyon channels in its amphitheater head. The "B" canyon channels merge into a single channel at the base of the slope, make two 90° turns, and then join the canyon-channel system C part way down the gentle-basin slope. The canyon-channel system typically referred to in the literature is

canyon-channel C ("C" in Fig. 9) that heads less than 300 m from shore in less than 8 m water depth. The canyon channel meanders across the shelf for 2 km to the shelf break where it is 500 m wide and 95 m deep. The canyon channel straightens down the 5° to 6° steep-basin slope to the 1° to 2° gentle-basin slope with a sharp horseshoe bend at ~290 m water depth. This channel loses its definition in the data ~15 km from its head.

The next system to the west, canyon-channel system D ("D" in Fig. 9) heads in a 1-km-wide amphitheater that incises 700 m

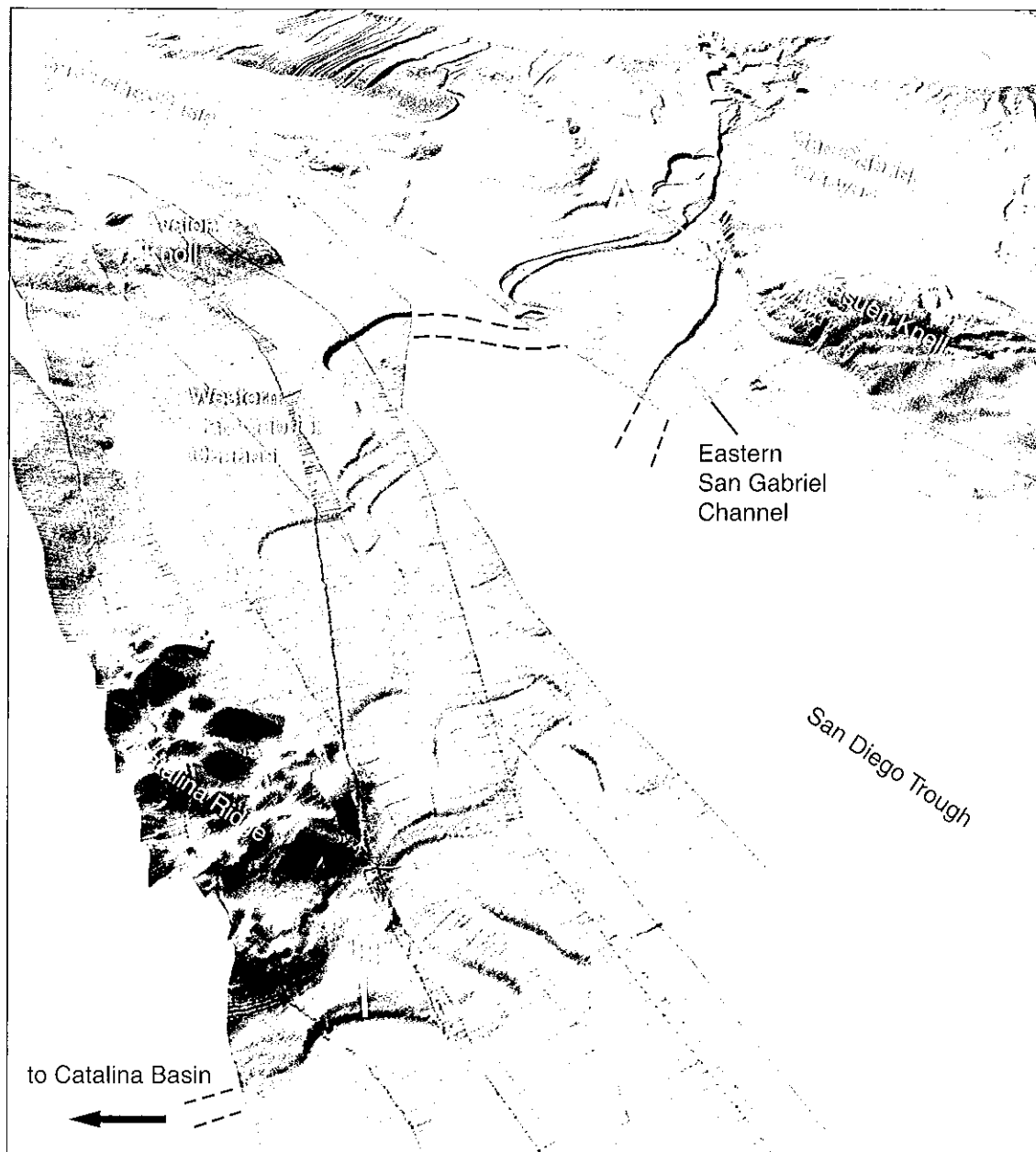


Figure 8. Perspective view of shaded bathymetry looking north at the lower reaches of the San Gabriel Canyon from where it splits into two channels at the northern end of Lasuen Knoll (A) to where the main channel wraps around the southern end of the Catalina Ridge (B). The vertical exaggeration is 2×, and the distance across the bottom of the image is ~12 km. See Figure 12 for the view direction.

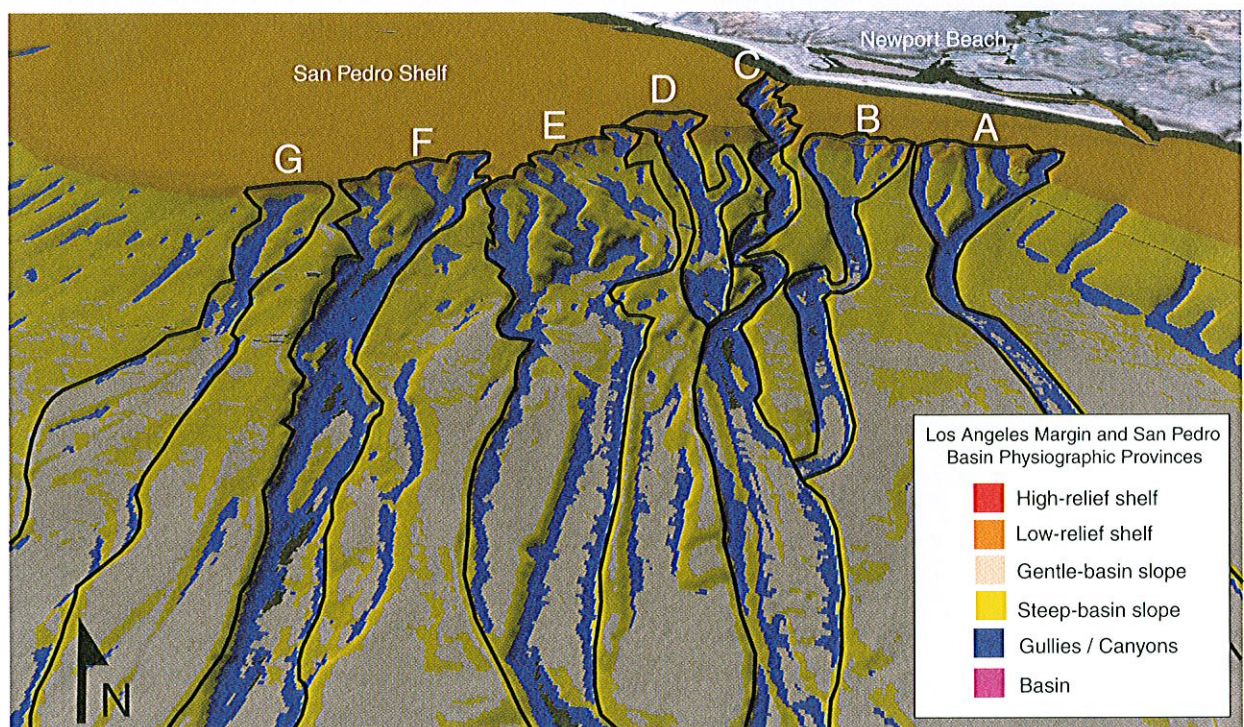
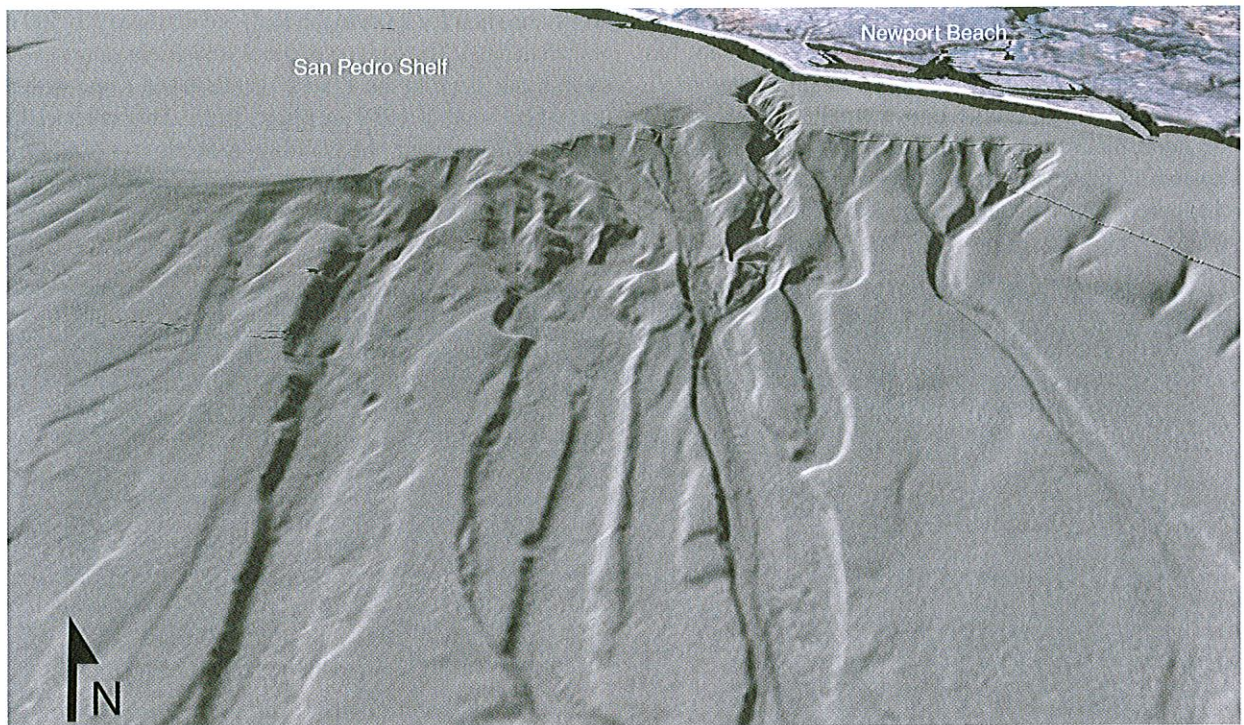


Figure 9. (A) Perspective view of shaded bathymetry looking north at the upper reaches of Newport Canyon. See Figure 12 for the view direction. The vertical exaggeration is 2x, and the distance across the bottom of the image is ~8 km. (B) The same perspective view as (A) with interpreted outlines of seven individual channels (segments A–G) within the Newport Canyon complex. Land displayed using Landsat-7 imagery.

into the shelf. System D starts out as a straight, 600-m-wide canyon channel that is captured by canyon-channel C at the base of the slope. Canyon-channel system E ("E" in Fig. 9) heads in a broad, 2-km-wide, amphitheater with four canyon channels that follow torturous paths for the first 3.7 km before being captured by the westernmost channel that is itself captured by canyon-channel system C. The two western canyon-channel systems of the Newport Canyon complex ("F" and "G" in Fig. 9) are relatively simple, canyon-channel systems compared to the others to the east. Each of these two systems can be traced for ~20 km downslope. System G is captured ~9 km downslope by canyon-channel system F. All of the canyon-channel systems of the Newport Canyon complex lose their bathymetric expression in the data after they were steered around Lasuen Knoll. However, lower resolution bathymetry data show that the channels merge into a single channel that can be traced into the San Diego Trough for a distance of 70 km.

The multiple channels of both the San Gabriel and Newport Canyons show the meandering nature of their ancestral river sources as the rivers flowed across the mainland shelf during lower sea-level stands and deposited sediment at the shelf break. This sediment periodically flowed down into the basins as turbidity currents cutting the various and meandering canyon channels. As with the smaller gullies, identifying the pathways of the canyons can help determine the final sink for material transported from the land and mainland shelf.

San Pedro Basin

The San Pedro Basin is small compared to the other basins within the Southern California Borderlands. It is ~35 km long northwest to southeast and 20 km wide northeast to southwest with a maximum depth of 905 m (Fig. 1). The basin is bounded on the south by the Catalina Ridge, on the west by Redondo Knoll and the Redondo Canyon delta, and on the east by Avalon Knoll and a series of northwest-southeast-trending ridges. The floor of the San Pedro Basin gently slopes to the southwest toward Catalina Island.

A sill with a minimum depth of 865 m ("A" on Fig. 10) extends from Catalina Ridge to Redondo Knoll to Redondo Canyon delta that separates the San Pedro Basin from the Santa Monica Basin. Redondo Knoll has a minimum depth of 503 m and rises over 400 m above the Santa Monica and San Pedro Basins. The knoll abruptly rises on its south and east sides, with cliffs along the knoll's east side that rise up to 250 m. The northwest slopes gently descend toward the Santa Monica Basin.

The Redondo Canyon delta (Fig. 6) is the largest delta of the four canyon-channel systems in the study area. The newly compiled, multibeam data in San Pedro Basin show that there are four delta channels. Yerkes et al. (1967) describe at least three, and Gardner et al. (2003) describe two. The most recently active channel (Gardner et al., 2003) ("C" on Fig. 10) leaves the canyon and immediately turns south along the basin slope for 3.3 km before it turns to the southwest into the San Pedro Basin, where it eventually loses its relief ~9.5 km from the mouth of the canyon.

An older channel ("D" on Fig. 10) strikes southwest from the mouth of the canyon toward the south side of Redondo Knoll. The 500-m-wide channel incises over 15 m into the deltaic sediment and has two channel features that resemble cataracts or plunge pools ("E" on Fig. 10) similar to those described by Gardner et al. (1997) from a channel on Monterey Fan and by Lee et al. (2002) from other areas of the U.S. margin. The channel loses its relief ~11 km from the mouth of the canyon. A third channel ("G" on Fig. 10) strikes west from the mouth of Redondo Canyon and flows onto Santa Monica Basin. A fourth, 500-m-wide channel ("H" on Fig. 10) flows to the base of the Redondo Knoll and appears to have been connected to channel D but became inactive when channel D turned to the south.

A northern sill separates the San Pedro Basin and Santa Monica Basin, but the southern boundary of the San Pedro Basin is less well defined. Although it appears there is a boundary composed of Avalon Knoll and a series of three northwest-southeast-trending mounds (Fig. 11), the MBES bathymetry shows that this is not the case. Avalon Knoll rises over 400 m above the San Pedro Basin and 300 m above the northern end of the San Diego Trough with a minimum water depth of 422 m. The three mounds rise from 50 m to 100 m above the surrounding seafloor. However, the northern end of the San Diego trough is ~100 m above the San Pedro Basin, and there are three passes in between Avalon Knoll and the mounds ("A" through "C" on Fig. 11) that slope northwest into San Pedro Basin.

Redondo Canyon is the northern limit of sediment supply into San Pedro Basin from the inland shelf region, whereas the southern limit is south of the San Pedro Sea Valley where three small gullies flow into a larger 150-m-wide gully ("E" in Fig. 6) that empties into the basin.

CONCLUSIONS

Advances in mapping technology over the past few decades allow the complete mapping of the seafloor with a high degree of accuracy so that reliable digital terrain models can be developed to interpret the geomorphology and sediment pathways of an area. Although the new digital terrain models reveal the vastly more complex nature of the bathymetry, it is that complexity of the bathymetry that will allow a reassessment of the processes that formed the bathymetry. Newly compiled, multibeam bathymetry from the San Pedro Basin as well as a terrain analysis for the entire Los Angeles region shows the seafloor offshore the greater Los Angeles area in detail. Derived bathymetric indices, including seafloor slope and Topographic Position Index, were analyzed using a hierarchical, decision-tree classification process. This terrain analysis identified rock outcrops protruding above the smooth continental shelf within Santa Monica Bay, offshore the Palos Verdes Peninsula, and along the outer San Pedro Shelf. The analysis also identified individual gullies, some with widths less than 60 m, incised into the steep basin slopes, as well as larger submarine canyons that extend for tens of kilometers.

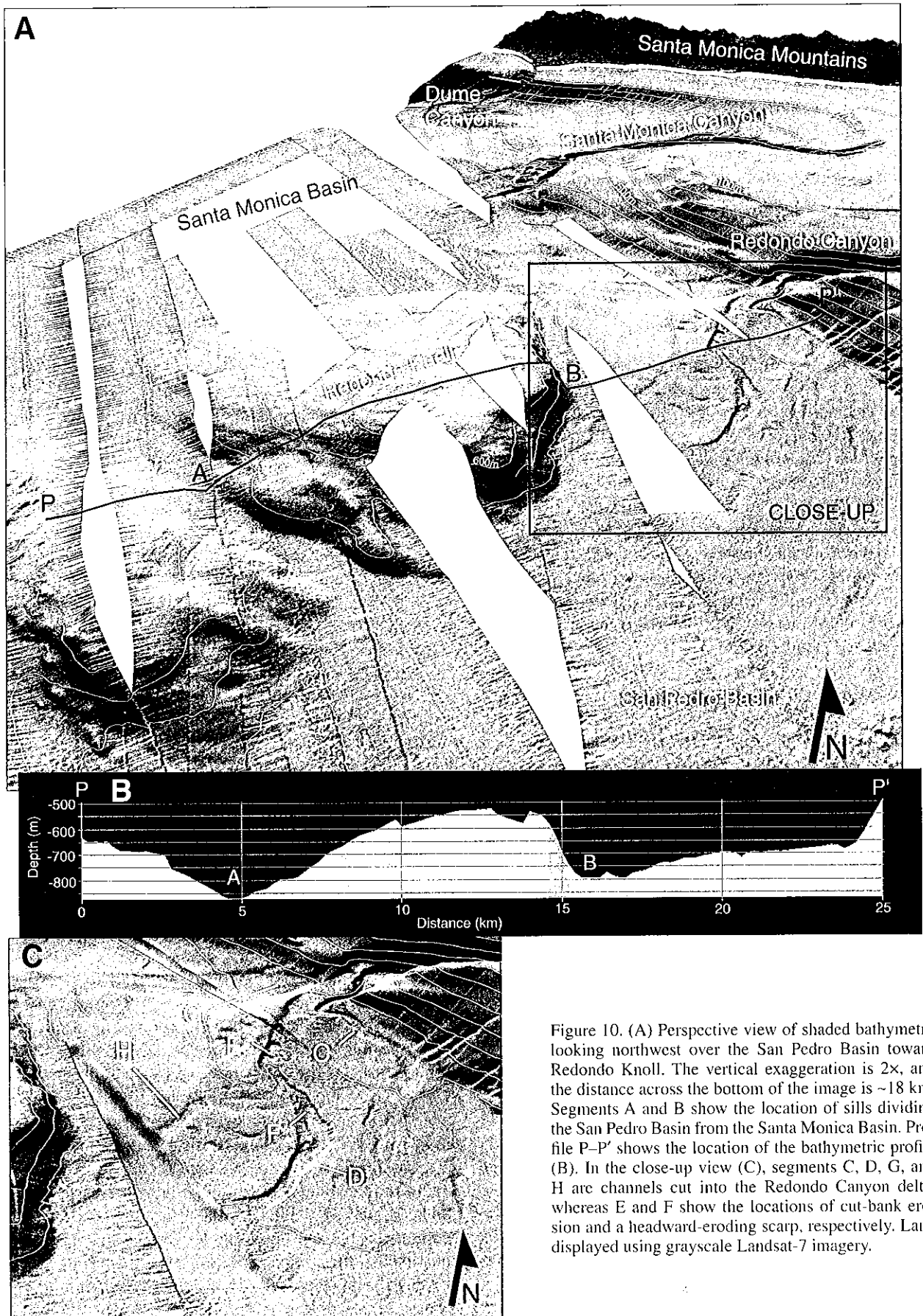


Figure 10. (A) Perspective view of shaded bathymetry looking northwest over the San Pedro Basin toward Redondo Knoll. The vertical exaggeration is 2x, and the distance across the bottom of the image is ~18 km. Segments A and B show the location of sills dividing the San Pedro Basin from the Santa Monica Basin. Profile P-P' shows the location of the bathymetric profile (B). In the close-up view (C), segments C, D, G, and H are channels cut into the Redondo Canyon delta, whereas E and F show the locations of cut-bank erosion and a headward-eroding scarp, respectively. Land displayed using grayscale Landsat-7 imagery.

Multibeam bathymetry within the San Pedro Basin shows that the basin is ~905 m deep and is separated from the Santa Monica Basin to the north by a ridge consisting of the Redondo Knoll and the Redondo Submarine Canyon delta. The minimum sill depth separating the two basins is 865 m. To the south, the San Pedro Basin is ~100 m deeper than the San Diego Trough, and three passes breach the ridge that separates the basin from the trough. The northern limit of sediment supply from the main-land shelf into the basin is through the Redondo Submarine Canyon, whereas the southern supply of sediment is from a series of gullies located between the San Pedro Sea Valley and the San Gabriel Submarine Canyon.

Even though the seafloor within Southern California has been studied for decades, the accurate digital terrain model compiled from this study, as well the identification and calculated aerial coverage of the six seafloor provinces, can be used as base map information for future studies, such as landscape evolution, regional tectonics, benthic habitats, and sediment-transport and pollution-transport models.

ACKNOWLEDGMENTS

The authors would like to thank Michael A. Fisher and H. Gary Greene for their thoughtful reviews of this manuscript.

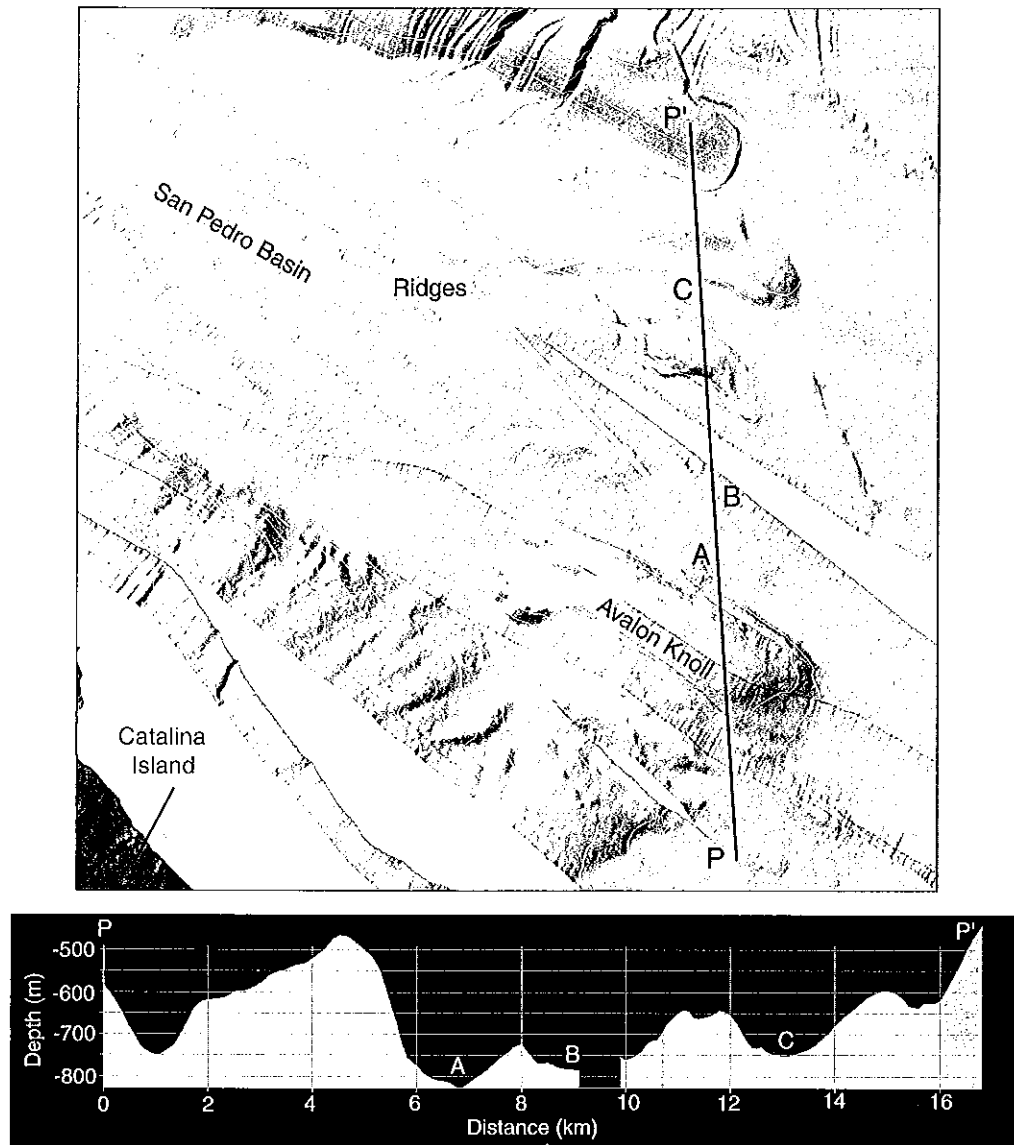


Figure 11. Shaded-bathymetry map view of the southeastern side of the San Pedro Basin in the location of Avalon Knoll. P-P' shows the location of the profile below the map. Segments A, B, and C, in both the map view and profile, show the locations of passes through the ridge separating the San Pedro Basin from the San Diego Trough. North is toward the top of the image.

APPENDIX A. MULTIBEAM BATHYMETRY DATA SETS

(1) The U.S. Geological Survey mapped the Santa Monica Bay region from Point Dume to Palos Verdes in 1996 using a Kongsberg Simrad EM1000 multibeam echo-

sounder (MBES) (95 kHz). Data and metadata available at: <http://pubs.usgs.gov/of/2004/1221/>.

(2) The U.S. Geological Survey mapped the basin slope off Palos Verdes as well as the San Gabriel and Newport Canyons in 1998 using a Kongsberg Simrad EM300 MBES

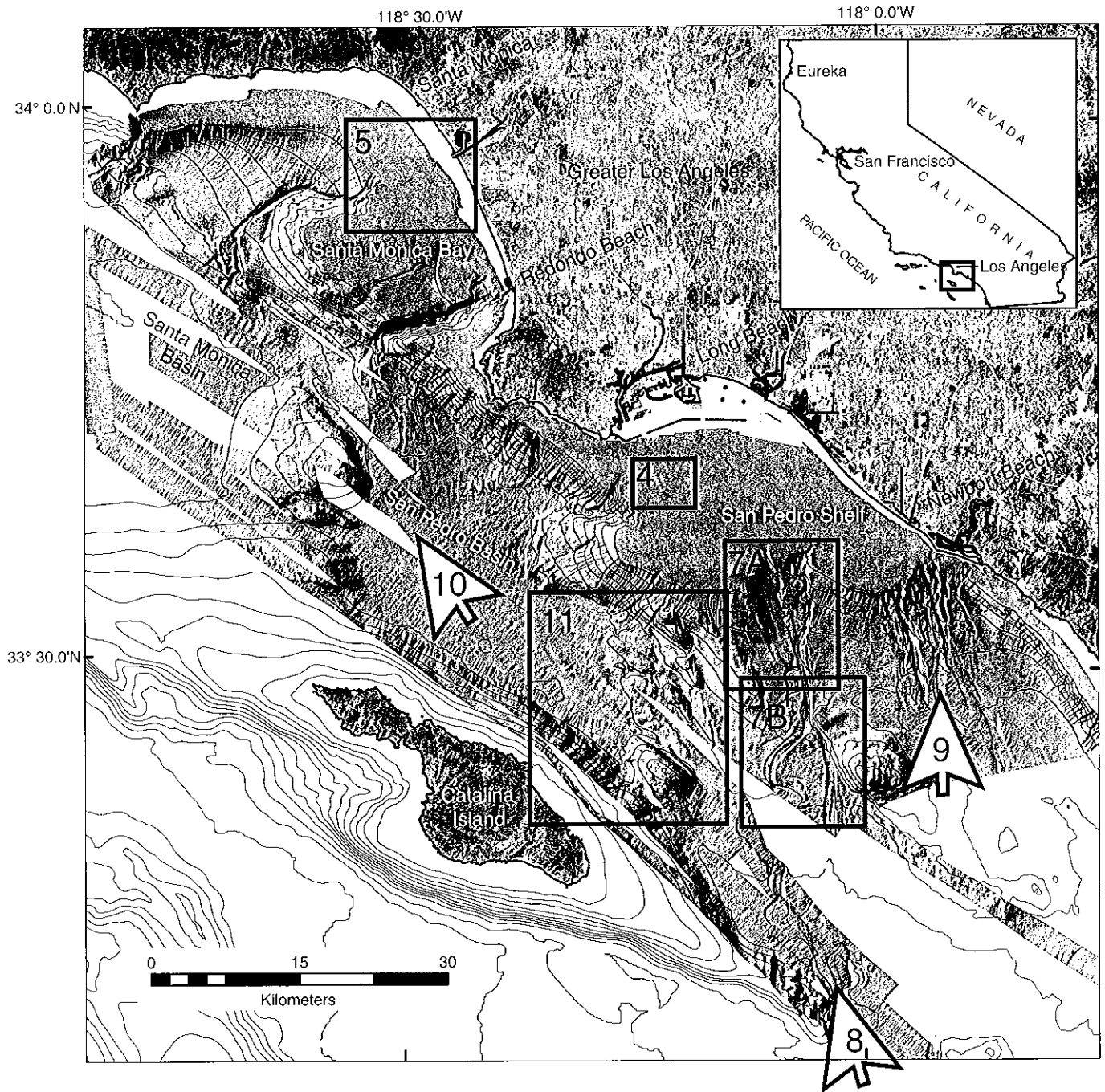


Figure 12. Index map of the viewing directions of Figures 4–11 (excluding Fig. 6). Black boxes show the locations of map views, whereas white arrows show the location and direction of perspective views. The numbers associated with each box or arrow corresponds to the figure number. Land displayed using grayscale Landsat-7 imagery.

- (30 kHz). Data and metadata available at: <http://geopubs.wr.usgs.gov/open-file/of02-162/>.
- (3) The U.S. Geological Survey mapped the San Pedro Shelf in 1999 using a Kongsberg Simrad EM3000D MBES (300 kHz). Data and metadata available at: <http://pubs.usgs.gov/of/2004/1221/>.
- (4) California State University–Monterey Bay, Seafloor Mapping Lab, mapped the nearshore regions in northern Santa Monica Bay as well as the near-shore regions around the Palos Verdes Peninsula in 2001 using a Reson 8101 (240 kHz). Data and metadata available at: http://seafloor.csusb.edu/SFMLwebDATA_s.htm. Data used in this study were acquired, processed, archived, and distributed by the Seafloor Mapping Lab of California State University–Monterey Bay.
- (5) The National Oceanographic and Atmospheric Administration mapped portions of the San Pedro Basin in 2000.
- (6) Transit data through the San Pedro Basin collected by the Scripps Institute of Oceanography including: (a) Cruise ID NPAL98MV, P. Worcester (Scripps), chief scientist, R/V *Melville*, 7/06/1998–7/18/1998 and (b) Cruise ID WEST15MV, S. Cande and J. Hildebrand, chief scientists, R/V *Melville*, 7/11/1995–8/12/1995. All data available from the National Geophysical Data Center at: <http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html>.

REFERENCES CITED

- Atwater, T.M., 1970, Implications of plate tectonics for the Cenozoic evolution of western North America: *Geological Society of America Bulletin*, v. 81, p. 3513–3536, doi: 10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2.
- Bjorklund, T., Burke, K., Zhou, H., and Yeats, R.S., 2002, Miocene rifting in the Los Angeles Basin: Evidence from the Puente Hills half-graben, volcanic rocks, and P-wave tomography: *Geology*, v. 30, no. 5, p. 451–454, doi: 10.1130/0091-7613(2002)030<0451:MRITLA>2.0.CO;2.
- Bohannon, R.G., and Gardner, J.V., 2004, Submarine landslides of San Pedro Escarpment, southwest of Long Beach, California: *Marine Geology*, v. 203, p. 261–268, doi: 10.1016/S0025-3227(03)00309-8.
- Bohannon, R.G., and Geist, E.L., 1998, Upper crustal structure and Neogene tectonic development of the California Continental Borderland: *Geological Society of America Bulletin*, v. 110, p. 779–800, doi: 10.1130/0016-7606(1998)110<0779:UCSANT>2.3.CO;2.
- Crouch, J.K., and Suppe, J., 1993, Late Cenozoic tectonic evolution of the Los Angeles Basin and inner California borderland—A model for core complex-like crustal extension: *Geological Society of America Bulletin*, v. 105, p. 1415–1434, doi: 10.1130/0016-7606(1993)105<1415:LCTEOT>2.3.CO;2.
- Dartnell, P., and Gardner, J.V., 1999, Seafloor images and data from multibeam surveys in San Francisco Bay, southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada: U.S. Geological Survey Digital Data Series DDS-55, version 1 (CD-ROM).
- Dartnell, P., and Gardner, J.V., 2004, Predicting seafloor facies from multibeam bathymetry and backscatter data: *Photogrammetric Engineering and Remote Sensing*, v. 70, no. 9, p. 1081–1091.
- Dickinson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California: *Geological Society of America Bulletin*, v. 109, p. 936–954, doi: 10.1130/0016-7606(1997)109<0936:OTIOCV>2.3.CO;2.
- Edwards, B.D., Dartnell, P., and Chezar, H., 2003, Characterizing benthic substrates of Santa Monica Bay with seafloor photography and multibeam sonar imagery: *Marine Environmental Research*, v. 56, no. 1–2, p. 47–66, doi: 10.1016/S0141-1136(02)00324-0.
- Emery, K.O., 1960, The sea off southern California: A modern habitat of petroleum: New York, John Wiley and Sons, 366 p.
- Emery, K.O., and Terry, D., 1956, A submarine slope off southern California: *The Journal of Geology*, v. 64, p. 271–280.
- ERDAS, 1999, Field Guide: Atlanta, Georgia, ERDAS, 672 p.
- Fisher, M.A., Normark, W.R., Langenheim, V.E., Calvert, A.J., and Sliter, R., 2004, Marine geology and earthquake hazards of the San Pedro Shelf region, southern California: U.S. Geological Survey Professional Paper 1687, 33 p.
- Gardner, J.V., and Mayer, L.A., 1998, Cruise Report: RV Ocean Alert Cruise A2-98-SC, Mapping the Southern California Continental Margin, March 26–April 11, 1998: U.S. Geological Survey Open-File Report 98-475, <http://geopubs.wr.usgs.gov/open-file/of98-475/> [18 April 2000].
- Gardner, J.V., Bohannon, R.G., Field, M.E., and Masson, D.G., 1997, The morphology, processes, and evolution of Monterey Fan: A revisit, in Gardner, J.V., Field, M.E., and Twichell, D.C., eds., *Geology of the United States seafloor: The view from GLORIA*: Cambridge University Press, p. 193–220.
- Gardner, J.V., Dartnell, P., Mayer, L.A., and Hughes Clarke, J.E., 1999a, Shaded-relief bathymetry and backscatter maps of Santa Monica Margin, California: U.S. Geological Survey Geologic Investigations Series Map I-2648 (2 map sheets).
- Gardner, J.V., Hughes Clarke, J.E., and Mayer, L.A., 1999b, Cruise Report: RV Coastal Surveyor Cruise C-1-99-SC, Multibeam mapping of the Long Beach, California, Continental Shelf: U.S. Geological Survey Open-File Report 99-360, <http://geopubs.wr.usgs.gov/open-file/of99-360/> [21 August 2001].
- Gardner, J.V., Dartnell, P., Stone, J.C., Mayer, L.A., and Hughes Clarke, J.E., 2002, Bathymetry and selected perspective views offshore greater Los Angeles, California: U.S. Geological Survey Water-Resources Investigations Report 02-4126 (1 map sheet).
- Gardner, J.V., Dartnell, P., Mayer, L.A., and Hughes Clarke, J.E., 2003, Geomorphology, acoustic backscatter and processes in Santa Monica Bay from multibeam mapping: *Marine Environmental Research*, v. 56, no. 1–2, p. 15–46, doi: 10.1016/S0141-1136(02)00323-9.
- Greene, H.G., Kivitek, R., Bizzarro, J.J., Bretz, C., and Iampietro, P., 2004, Fisheries habitat characterization of the California Continental Margin: California Sea Grant College Program, CD-ROM.
- Hampton, M.A., Karl, H.A., and Murray, C.J., 2002, Acoustic profiles and images of the Palos Verdes margin: Implications concerning deposition from the White's Point outfall: *Continental Shelf Research*, v. 22, p. 841–857.
- Hanc, B.E., and Gorsline, D.S., 1978, Processes and morphology of continental slope between Santa Monica and Dume Submarine Canyons, southern California: *Marine Geology*, v. 28, p. 77–87, doi: 10.1016/0025-3227(78)90098-1.
- Hughes Clarke, J.E., 2000a, Acoustic seabed surveying—Meeting the new demands for accuracy, coverage, and spatial resolution: *Geomatica*, v. 54, p. 473–513.
- Hughes Clarke, J.E., 2000b, Present-day methods of depth measurements: Continental shelf limits, in Cook, P.J., and Carleton, C.M., eds., *The scientific and legal interface*: Oxford University Press, p. 139–159.
- Hughes Clarke, J.E., Mayer, L.A., and Wells, D.E., 1996, Shallow-water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf: *Marine Geophysical Researches*, v. 18, p. 607–629, doi: 10.1007/BF00313877.
- Iampietro, P.J., Kivitek, R.G., and Morris, E., 2005, Recent advances in automated genus-specific marine habitat mapping enabled by high-resolution multibeam bathymetry: *Marine Technology Society Journal*, v. 39, no. 3, p. 83–93.
- Kivitek, R.G., Leisten, T.M., Iampietro, P.J., and Bretz, C.K., 2003, Santa Monica Bay mapping project: Final Report and GIS User's Guide: http://seafloor.csusb.edu/publications/SMBMP_Final_Report.pdf.
- Lee, H.J., Kayen, R.E., Gardner, J.V., and Locat, J., 2003, Characteristics of several tsunamigenic submarine landslides, in Locat, J., and Mienert, J., eds., *Submarine mass movements and their consequences*: Kluwer Academic Publishers, p. 357–366.
- Lee, S.E., Talling, P.J., Ernst, G.G.J., and Hogg, A.J., 2002, Occurrence and origin of submarine plunge pools at the base of the U.S. continental slope: *Marine Geology*, v. 185, p. 363–377, doi: 10.1016/S0025-3227(01)00298-5.
- Leecaster, M., 2003, Spatial analysis of grain size in Santa Monica Bay: *Marine Environmental Research*, v. 56, p. 67–78, doi: 10.1016/S0141-1136(02)00325-2.
- Locat, J., Locat, P., Lee, H.J., and Inman, J., 2004, Numerical modeling of the mobility of the Palos Verdes debris avalanche, California, and its

- implication for the generation of tsunamis: *Marine Geology*, v. 203, no. 3–4, p. 269–280, doi: 10.1016/S0025-3227(03)00310-4.
- Marlow, M.S., Gardner, J.V., and Normark, W.R., 2000, Using high-resolution multibeam bathymetry to identify seafloor surface rupture along the Palos Verdes fault complex in offshore southern California: *Geology*, v. 28, no. 7, p. 587–590, doi: 10.1130/0091-7613(2000)28<587:UHMBT>2.0.CO;2.
- McNeilan, T.W., Rockwell, T.K., and Resnik, G., 1996, Style and rate of Holocene, Palos Verdes Fault Zone, Southern California: *Journal of Geophysical Research*, v. 101, p. 8317–8334, doi: 10.1029/95JB02251.
- 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, doi: 10.1130/0091-7613(1994)022<0491:MCROTW>2.3.CO;2.
- Normark, W.R., McGann, M., and Sliter, R., 2004, Age of the Palos Verdes submarine debris avalanche, southern California: *Marine Geology*, v. 203, no. 3–4, p. 247–259, doi: 10.1016/S0025-3227(03)00308-6.
- Saucedo, G.J., Greene, H.G., Kennedy, M.P., and Bezore, S.P., 2009, Geologic map of the Long Beach 30' × 60' quadrangle: A digital database: *Regional Geologic Map Series*, scale: 1:100,000 (in press).
- Shepard, F.P., and Emery, K.O., 1941, Submarine topography off the California coast: Canyons and tectonic interpretations: *Geological Society of America Special Paper* 31, 171 p.
- Sommerfield, C.K., and Lee, H.J., 2003, Magnitude and variability of Holocene sediment accumulation in Santa Monica Bay, California: *Marine Environmental Research*, v. 56, p. 151–176, doi: 10.1016/S0141-1136(02)00329-X.
- ten Brink, U.S., Zhang, J., Brocher, T.M., Okaya, D.A., Klitgord, K.D., and Fuis, G.S., 2000, Geophysical evidence for the evolution of the California Inner Continental Borderland as a metamorphic core complex: *Journal of Geophysical Research*, v. 105, no. B3, p. 5835–5857, doi: 10.1029/1999JB900318.
- Weiss, A.D., 2001, Topographic position and landforms analysis: San Diego, California, Environmental Systems Research Institute (ESRI) User Conference, poster presentation.
- Wolf, S.C., and Gutmacher, C.E., 2004, Geologic and bathymetric reconnaissance overview of the San Pedro Shelf region, southern California: U.S. Geological Survey Open-File Report 2004-1049, <http://pubs.usgs.gov/of/2004/1049/>.
- Wright, D.J., Lundblad, E.R., Larkin, E.M., Rinehart, R.W., Murphy, J., Cary-Kothesa, L., and Draganov, K., 2005, ArcGIS Benthic Terrain Modeler: Corvallis, Oregon, Oregon State University Davey Jones Locker Seafloor Mapping/Marine GIS Laboratory and National Oceanic and Atmospheric Administration Coastal Services Center (<http://www.csc.noaa.gov/products/btm/>).
- Wright, T.L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, California, in Biddle, K.T., ed., *Active margin basins: American Association of Petroleum Geologists Memoir*, v. 52, p. 35–134.
- Yerkes, R.F., Gorsline, D.S., and Ruysnak, G.A., 1967, Origin of Redondo Submarine Canyon, Southern California: U.S. Geological Survey Professional Paper 575-C, p. C97–C105.

MANUSCRIPT ACCEPTED BY THE SOCIETY 5 NOVEMBER 2008