Geomorphology, acoustic backscatter, and processes in Santa Monica Bay from multibeam mapping

James V. Gardner[a,*], Peter Dartnell[a], Larry A. Mayer[b],
John E. Hughes Clarke[c]

[a]US Geological Survey, MS 999, 345 Middlesfied Road, Menlo Park, CA, 94025, USA
[b]University of New Hampshire, Durham, New Hampshire, USA
[c]University of New Brunswick, Fredericton, NB, Canada

Abstract

Santa Monica Bay was mapped in 1996 using a high-resolution multibeam system, providing the first substantial update of the submarine geomorphology since the initial compilation by Shepard and Emery [(1941) Geol. Soc. Amer. Spec. Paper 31]. The multibeam mapping generated not only high-resolution bathymetry, but also coregistered, calibrated acoustic backscatter at 95 kHz. The geomorphology has been subdivided into six provinces; shelf, marginal plateau, submarine canyon, basin slope, apron, and basin. The dimensions, gradients, and backscatter characteristics of each province is described and related to a combination of tectonics, climate, sea level, and sediment supply. Fluctuations of eustatic sea level have had a profound effect on the area; by periodically eroding the surface of Santa Monica plateau, extending the mouth of the Los Angeles River to various locations along the shelf break, and by connecting submarine canyons to rivers. A wetter glacial climate undoubtedly generated more sediment to the rivers that then transported the increased sediment load to the low-stand coastline and canyon heads. The trends of Santa Monica Canyon and several bathymetric highs suggest a complex tectonic stress field that has controlled the various segments. There is no geomorphic evidence to suggest Redondo Canyon is fault controlled. The San Pedro fault can be extended more than 30 km to the northwest by the alignment of a series of bathymetric highs and abrupt changes in direction of channel thalwegs.
Published by Elsevier Science Ltd.

Keywords: Geomorphology; Submarine canyons; Multibeam; Backscatter; California borderland

---

* Corrresponding author. Tel.: +1-650-329-5469.
  E-mail address: jvgardner@usgs.gov (J.V. Gardner).

Contents

1. Introduction

The submarine geomorphology of Santa Monica Bay (Fig. 1) has been known on a broad scale since the pioneering works of Shepard and Emery (1941) and Emery (1960). These studies, as well as subsequent studies of some of the dominant features of the bay (e.g. Haner & Gorsline, 1978; Terry & Stevenson, 1957; Yerkes, Gorsline, & Ruysnak, 1967), interpreted the submarine geomorphology from sparsely spaced single-beam echo sounder survey lines. Water depths were compiled, contour lines were hand-drawn, and the large-scale geomorphic features emerged. In the five decades since the publication of the Shepard and Emery (1941) map, little has been added to the detailed geomorphology because, up to the 1990s, seafloor-mapping tools had remained essentially unchanged. However, with the introduction of high-
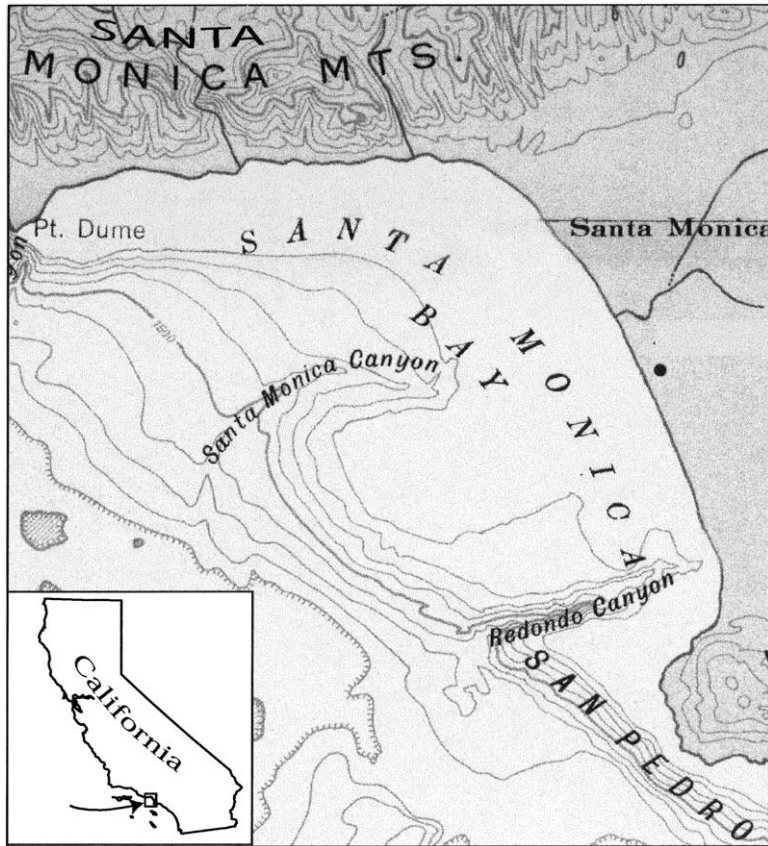
Fig. 1. Shepard and Emery (1941) bathymetric map of Santa Monica Bay (slightly modified). Contours interval 300 ft. This map has been the base map for all subsequent studies in Santa Monica Bay.

resolution multibeam mapping systems in the mid 1990s (Hughes Clarke, Mayer, & Wells, 1996; Mayer, Hughes Clark, & Dijkstvc, 1997), a revolutionary new type of mapping system for shelf and slope depths became available. Now, instead of interpolating between a series of survey tracks, dense soundings can be collected from the entire seafloor and virtually no interpolation is required to produce the details of the physiographic surface.

An equally revolutionary development occurred along with the ability to map the bathymetry; calibrated acoustic backscatter from multibeam systems. Calibrated acoustic backscatter as an integral component of a multibeam echo sounder provides a backscatter image that is precisely georeferenced and coregistered to the multibeam bathymetry and thus can be corrected for topographic relief as measured by the multibeam, corrected for beam-pattern, gain changes, changes in pulse-length, and compensated for ensonified area and absorption losses. Multibeam backscatter data, coupled with adequate ground-truth samples can provide impor-

tant insights into the surficial geology of the seafloor. These advances, coupled with advances in computer technology, vehicle motion sensors, and precise navigation, provide unprecedented data sets with which to investigate the quantitative geomorphology of the seafloor.

In 1996 the US Geological Survey and the University of New Brunswick conducted extensive seafloor mapping of Santa Monica Bay (Fig. 2) with a state-of-the-art high-resolution multibeam mapping system. This effort produced bathymetric and acoustic-backscatter maps of virtually 100% of Santa Monica Bay between the 20- and 800-m isobaths at spatial resolutions that vary from 2 to 16 m, depending on water depth. Image-processing and analysis techniques allow the visualization of these vast data sets in their entirety and the quantitative description of the submarine geomorphology.

This study describes the various submarine physiographic provinces found in Santa Monica Bay as well as discusses the acoustic backscatter of the area. Because the huge bathymetry and backscatter data sets are necessarily visual, the submarine geomorphology and its relationship to the geology is best appreciated in oblique, perspective views.

2. Multibeam mapping systems

The 1996 mapping used a Kongsberg Simrad EM1000 multibeam system coupled with a TSS/Applied Analytic POS/MV motion reference unit, a Trimble 4000 dual DGPS with Skyfix satellite reference, and a SeaBird SBE-19 CTD profiler. The details of the multibeam sonar can be found in Hughes Clarke et al. (1996) and Mayer et al. (1997). Briefly, the EM1000 multibeam system transmits a narrow (0.7 or 2.0 ms) acoustic pulse. The receive array is composed of 48–60 (depending on water depth) adjacent $2.5° \times 3.5°$ apertures (referred to as "beams"). The receive array uses both the center of mass of the returned echo for each beam and an interferometric phase-detection principle to determine depth. A time series of echo amplitudes from each beam is processed from beam to beam to produce a backscatter image that resembles a side-scan-sonar record. Because the angular direction of each range sample is precisely known, the amplitude information can be placed in its geometrically correct position relative to the across-track profile. The system corrects the amplitude time series for each beam for gain changes, propagation losses, predicted beam patterns and for the ensonified area. Subsequent processing applies empirically derived beam-pattern corrections to produce a quantitative estimate of seafloor backscatter across the swath.

The roll, pitch, yaw, and heave of the vessel was measured by the motion reference unit at 50 Hz and the multibeam processor applied compensations for these attitudes. The bathymetric data were reduced to mean lower low water based on the semidiurnal tides measured at the Santa Monica pier. The navigation systems, interfaced with the motion reference unit, provide position accuracy of about ± 1 m for each ray-traced beam path sounding.
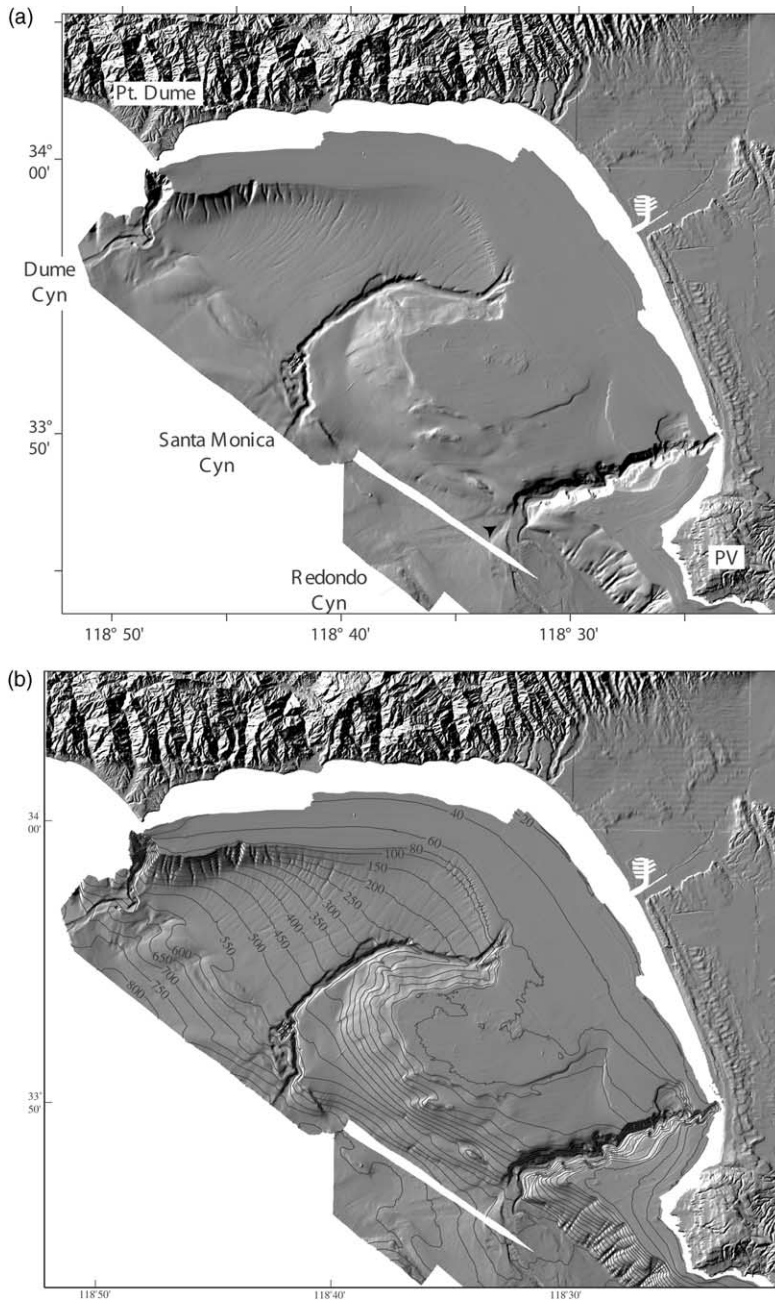
Fig. 2. (a) Plan view of shaded-relief of Santa Monica Bay from 1996 multibeam mapping. Land shaded relief is from USGS 30-m DEM. (b) Same map as in (a) but with contours; 20-m contour interval 0–100-m and 50-m contour interval for deeps greater than 100 m. PV indicates Palos Verdes Peninsula.

3. Data sets

Contour maps of bathymetry represent the more traditional method of displaying bathymetry. However, more than 90% of the multibeam data would be discarded if the data were displayed as contours. A much better representation of bathymetry, using 100% of the multibeam data to create a gridded digital terrain model, is a shaded-relief map (Fig. 2). A shaded-relief map is a pseudo-illumination of a topographic surface using the Lambertian scattering rule $SI = K*\cos^2 \Phi$, where SI is the pseudo-illumination intensity at a pixel, K is a constant that allows for even background, and Φ, is the angle between the pseudo-illumination source and the bathymetric surface.

A backscatter map (Fig. 3) is a representation of the amount of acoustic energy (at 95 kHz for this study) that is scattered back to each beam of the receiver array, referenced to the energy of the transmitted pulse at 1 m from the transducers. The amount of backscattered energy, measured in decibels (dB), is a complex function of constructive and destructive interference caused by the interaction of an acoustic wave with a volume of sediment or, in the case of hard rock, the seabed (Gardner, Field, Lee, Edwards, Masson, Venyon, & Kidd, 1991). The backscatter is the composite of contributions from surface roughness above the Rayleigh criteria (a function of frequency) and the acoustic "hardness" that is a function of the composition and bulk properties (elastic moduli, and mechanical properties). At 95 kHz, there also may be a contribution from volume reverberation and scattering because this
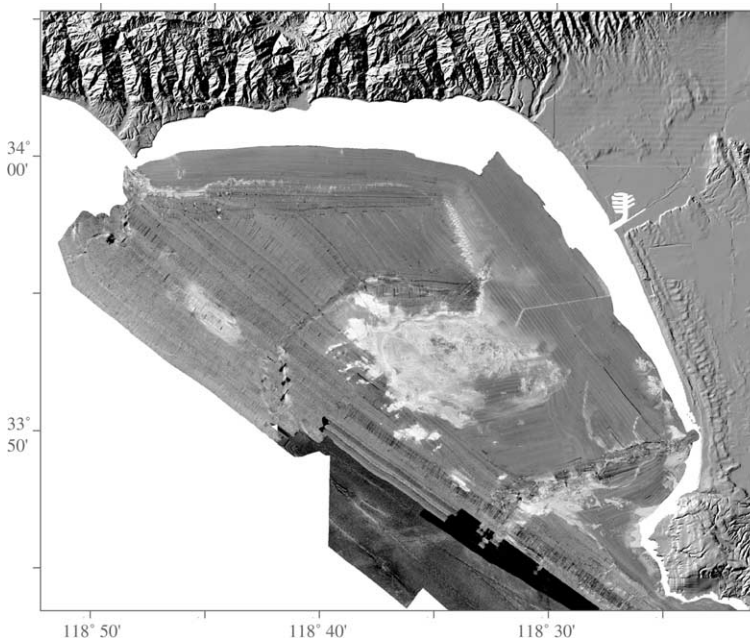

Fig. 3. Plan view of acoustic (95 kHz) backscatter of Santa Monica Bay from 1996 multibeam mapping. Lighter tones are higher backscatter. Land shaded relief was generated from USGS 30-m DEM.

frequency may penetrate as much as 10 cm below the seafloor (Mayer, Hughes Clarke, Wells and HYDRO-92 Team, 1993; Mitchell, 1993). The measured back-scatter values have been converted to 8-bit digital numbers (DN) for display purposes, with 0 dB = 255 DN (white) and −128 dB = 0 DN (black).

4. Submarine geomorphology

Although often cited as the continental margin, Santa Monica Bay occurs within a complex continental borderland (Shepard & Emery, 1941) more than 200 km east of the actual continental margin. The two regions have many geomorphic elements in common even though the borderland environment occurs in depths much shallower than the continental margin. Consequently, common marine geomorphic names have been used to discuss the geomorphology. We have subdivided the submarine geomorphology of Santa Monica Bay into six physiographic provinces principally defined by water depth and surface gradient. The provinces include shelf, marginal plateau, submarine canyon, basin slope, apron, and basin (Fig. 4). Some of the boundaries between adjacent provinces have been arbitrarily drawn because of the complex geology of the area and the provinces are not necessarily contiguous.
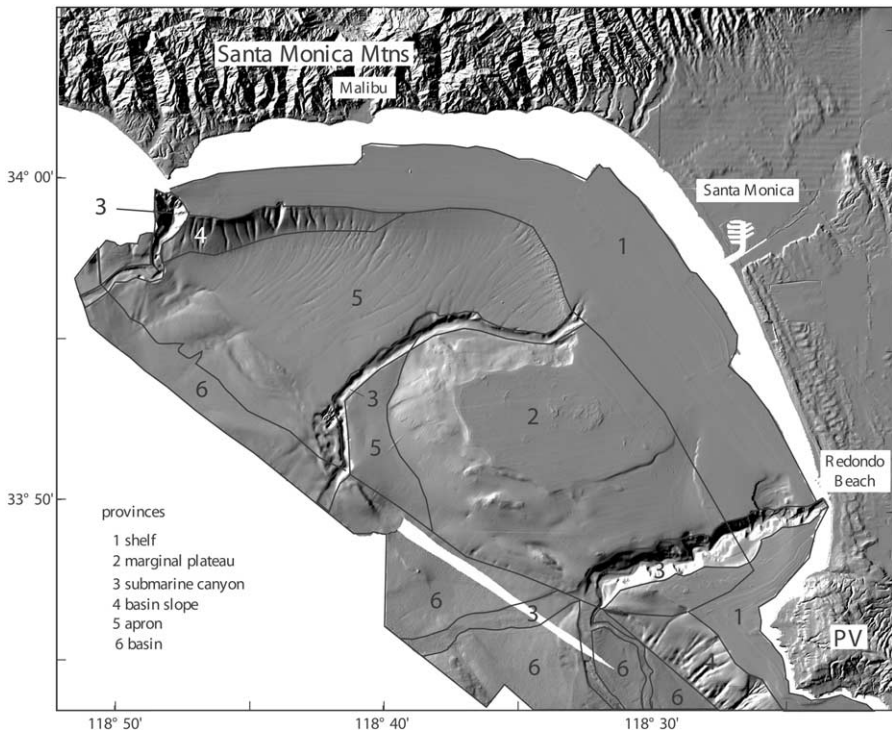

Fig. 4. Physiographic provinces of Santa Monica Bay defined by gradient drawn on shaded-relief map. PV indicates Palos Verdes Peninsula.

4.1. Shelf province

The shelf province extends seaward from the coastline to an abrupt change in gradient at about the 100-m isobath (Figs. 5 and 6). In general, the shelf in Santa Monica Bay is very flat and narrow. Shelf widths vary from 5 km off the Malibu margin to 10 km where the shelf grades into the northern side of the marginal plateau province. Shelf gradients generally are less than 0.5°, although there are several localized zones of rock outcrops adjacent to Palos Verdes Peninsula that produce gradients of more than 85° (Fig. 6). Outcrops occur on the outer Malibu shelf, along the inner shelf between Santa Monica and Redondo Beach, and all along the shelf west of the Palos Verdes Peninsula. Outside the outcrop zones, the shelf is essentially smooth. Backscatter from the shelf is typically very low, averaging about −35 dB, although the localized rock outcrops produce high backscatter (−20 dB). A zone of relatively high backscatter (−25 dB) occurs on the inner shelf from 33° 43.8′N to 33° 53′N (Fig. 3) around the Palos Verdes Peninsula (Fig. 7).

The shelf province is cut by numerous incisions of various sizes, the biggest of which are Santa Monica, Redondo, and Dume Canyons (Fig. 2a) (see discussions later). Dume and Redondo Canyons incise across the entire width of the shelf. A cirque-shaped reentrant of the shelf occurs on the northern flank of Redondo Canyon between the 80- and 150-m isobaths. This incision is 1500 m wide, 5000 m long, and as much as 300 m deep. Non-canyon incisions along the outer shelf edge south of the Malibu margin cut back into the shelf less than 300 m (Fig. 8). One of the few examples of a complex shelf incision is found just west of Palos Verdes Peninsula.
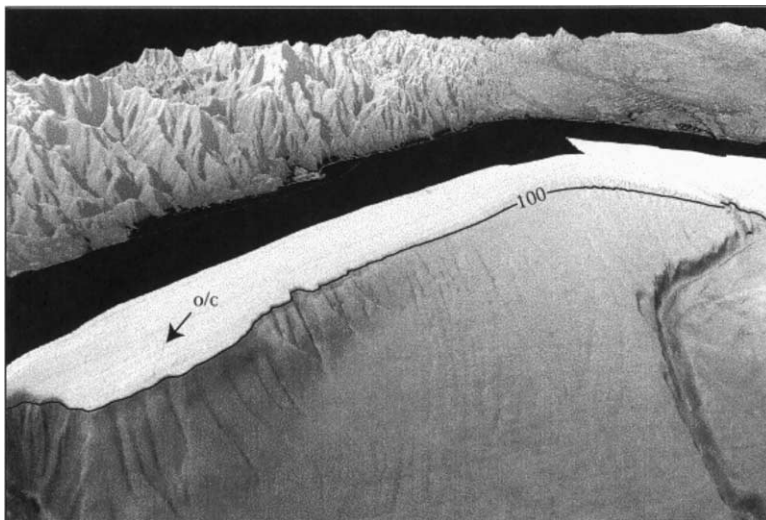

Fig. 5. Oblique shaded-relief view of Malibu shelf. View azimuth 050°. Arrow points to outcrops (o/c). 100-m isobath shown for reference. Vertical exaggeration 5×. Land shaded relief was generated from USGS 30-m DEM. See Appendix for location. Distance across bottom 15 km.
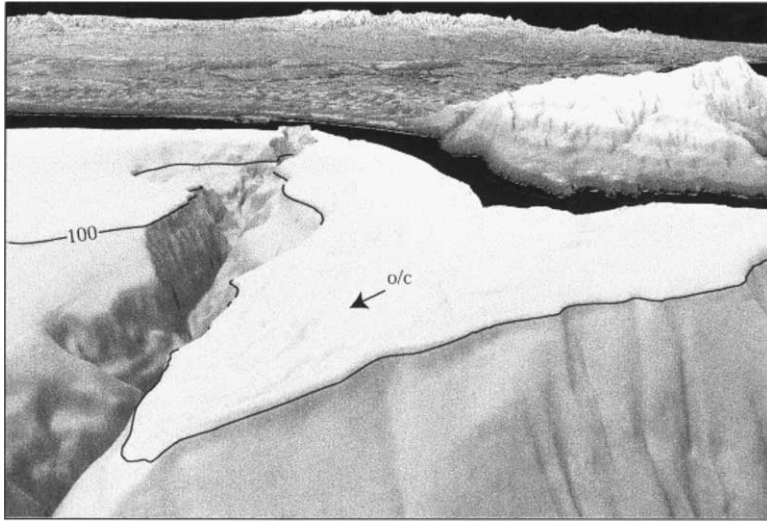
Fig. 6. Oblique shaded-relief view of southwest Palos Verde shelf. Redondo Canyon trends from lower left corner. View azimuth 045°. Arrow points to outcrops (o/c). 100-m isobath shown for reference. Vertical exaggeration 5×. Land shaded relief was generated from USGS 30-m DEM. See Appendix for location. Distance across bottom of image 8.4 km.

This feature is composed of at least 6 separate tributary-channel heads that have cut back 700 m into the shelf and 1700 m across the outer shelf (Fig. 9).

4.2. Marginal plateau province

The marginal plateau province is unique for the entire southern California margin. Although several isolated plateaus and banks occur within the borderland, the marginal plateau in Santa Monica Bay is the only one that is directly connected to the shelf. The plateau, called here Santa Monica plateau, has been called by others the Santa Monica shelf projection (Hauksson & Saldivar, 1989; Nardin & Henyey, 1978). The plateau is about 8.5 km north–south by 19 km east–west and the top of the plateau occurs between the 55- and 130-m isobaths (Fig. 10). The surface of Santa Monica plateau is inclined 0.2° to the west-southwest and encompasses a large region of rock outcrops (Terry & Stevenson, 1957). The outcrops rise as much as 14 m above the surrounding plateau surface. The plateau is bordered on the north by the Santa Monica Canyon and on the south by the Redondo Canyon. The Santa Monica plateau has a 15- to 20-m high steep zone around its edges with basin slopes of 8° to 10° in water depths of 90–110 m. The western margin of the plateau is excluded from the basin slope province because the style of erosion is unique to the plateau. The western margin of the plateau has very smooth basin slopes that range from 4.5° to 8° compared to the 11° to 20° basin slopes of the Malibu and Palos Verdes margin (Fig. 11).
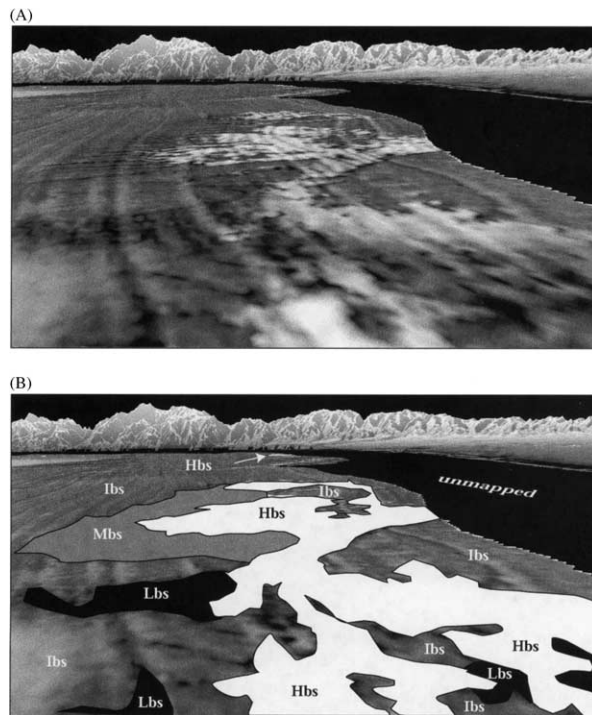
Fig. 7. (a) Oblique view of backscatter draped over bathymetry of inner shelf just offshore Santa Monica showing the complex pattern suggesting outcrops. (b) interpretation of oblique view; Hbs-high backscatter (−20 to −25 dB), Lbs-low backscatter (−35 to −37 dB), Ibs-intermediate backscatter (−25 to −35 dB), Mbs-linear alternation of high (−22 dB) and intermediate (−30 dB) backscatter View azimuth 010°. Vertical exaggeration 5×. Land shaded relief was generated from USGS 30-m DEM. See Appendix for location. Distance across bottom of image 800 m.

The acoustic backscatter from the surface of Santa Monica plateau has a very high variability, ranging from −17 to −37 dB. The low-backscatter regions (−35 to −37 dB) are found around the periphery of the plateau (Fig. 3) in flat and essentially featureless terrain. However, the central section of the plateau has a zone of very high backscatter (−17 to −20 dB) in an area with small-scale (<5 m) relief. Outcrops in this region are shown on a high-resolution seismic profiles that crosses the plateau (Fig. 12), showing a series of steeply folded anticlines and synclines (Hauksson & Saldivar, 1989; Nardin & Henyey, 1978) with strong seismic reflectors that correlate with zones of high backscatter (Dartnell, 2000). High backscatter is not confined to the top of the plateau but also occurs on the northern and southern flanks as well.

The southern boundary between Santa Monica plateau and the shelf (Fig. 4) is difficult to determine from the data. The plateau depths on either side of Redondo Canyon are identical. The backscatter data suggest the plateau area immediately south of Redondo Canyon is rock outcrop and the high backscatter continues in a
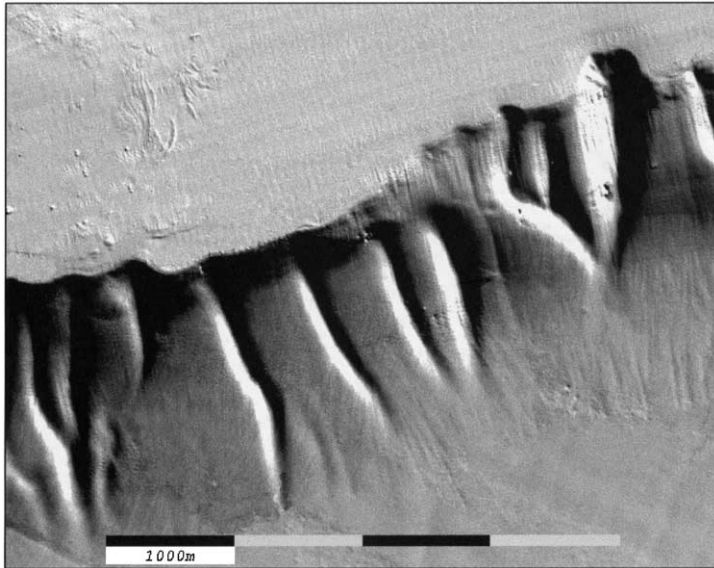
Fig. 8. Plan view of shaded-relief of outer shelf incisions and channels along Malibu margin. See Appendix for location.

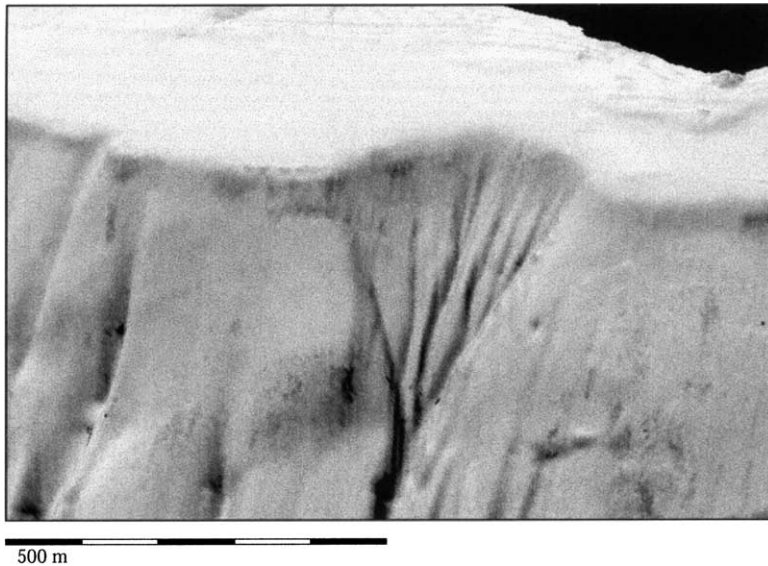Fig. 9. Plan view shaded relief of outer shelf incision along Palos Verdes shelf. See Appendix for location.

narrow band on the north side of the canyon (Fig. 13). However, the main reason for including the small area south of Redondo Canyon in the marginal plateau province is the striking lack of incisions on this section of the basin slope (compare with southern basin slope province in Fig. 4).
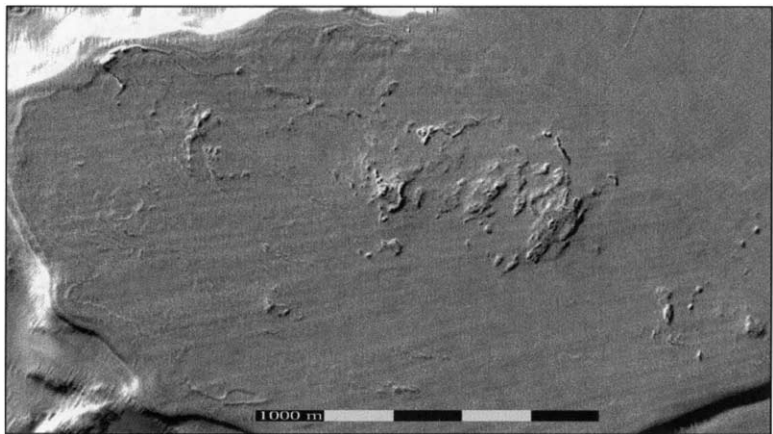
Fig. 10. Plan view of shaded-relief of top of Santa Monica plateau. Outcropping Miocene rock clearly shown by high relief. See Appendix for location.
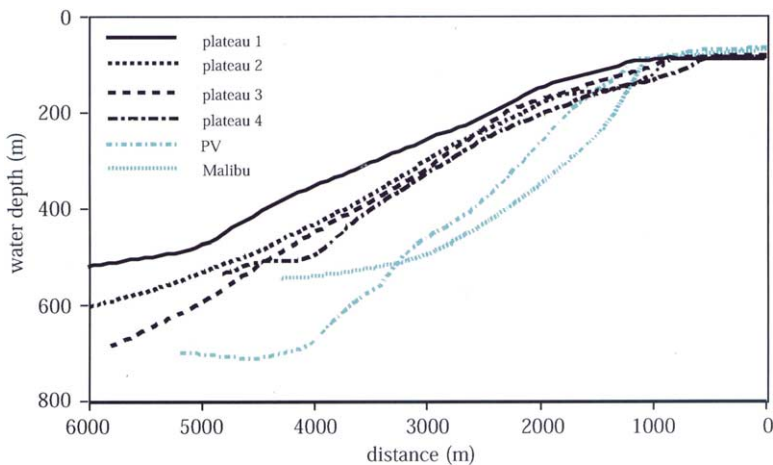

Fig. 11. Four bathymetric profiles (plateau 1–4) across western margin of Santa Monica plateau compared to profiles across Palos Verdes margin (PV) and Malibu margin (Malibu). Notice how steep the PV and Malibu margins are compared to the others.

A broad, gently sloping, valley occurs on the southeastern side of the plateau that increases in width and depth toward Redondo Canyon (Figs. 13 and 14). This valley is 1100 m wide at its narrowest and expands to more than 10-km wide. A linear distributary system traverses south down the valley, dividing into four distributaries by the middle of the valley. The distributary begins at the 54-m isobath and continues to the 164-m isobath where it plunges into Redondo Canyon.
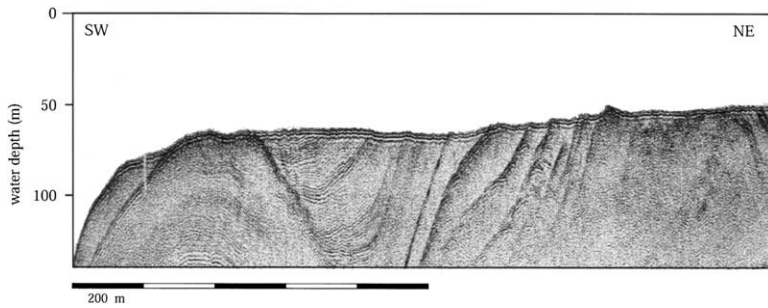
Fig. 12. Deep-towed high-resolution Huntec CHIRP profiler record across Santa Monica plateau. See Appendix for location of profile. Note outcropping limb of syncline on the northeast and the dip slope of the southwest margin. See Appendix for location.

4.3. Submarine canyon province

Three major submarine canyons, Santa Monica, Redondo, and Dume Canyons, occur within Santa Monica Bay (Fig. 4), each with its own distinctive morphology.

4.3.1. Santa Monica Canyon

Santa Monica Canyon incises the outer edge of the shelf with a complex of four head tributaries (Fig. 15) that begin between the 64- and 80-m isobaths and combine by the 250-m isobath to form a single submarine canyon. The main canyon channel is composed of five relatively straight segments that are 2800, 5850, 7500, and 3850 m in length, progressing from canyon head to mouth (Fig. 16). The junction of each segment trends 45–60° away from the preceding segment. Segments 1, 3, and 5 are all roughly parallel to one another on a trend of ~033°. Segments 1 and 5 are in line whereas segment 3 is parallel to, but offset ~4 km to the northwest of, a line connecting segments 1 and 5. The gradients of the segments range from 2.2° in segment 1 (68–253 m water depth) to 1.8° in segment 2 (253–422 m depth); 1.2° in segment 3 (422–599 m depth), and 1.9° in segment 4 (599–739 m depth) (Fig. 17 a). The thalweg profile shows a 1000 m-long zone of reduced gradients starting at about 8000 m from the channel head (* on Fig. 17b) that correlates to a zone of reduced thalweg width suggesting landslides have blocked or reduced the width of the channel in this zone. The overall thalweg profile changes from concave to convex at 10.2 km down channel directly opposite a large wall failure ("a" in Fig. 16). The convex zone correlates with an area of numerous failures of the north wall. The thalweg segments are only slightly sinuous (sinuosity indices of 0.97, 0.86, 0.88, 0.81, and 0.78 for segments 1–5, respectively (where sinuosity index is defined as the ratio of straight-line length of the channel to the length along the meandering channel), and exhibit relatively low backscatter (–37 dB). In general, the width of the thalweg, measured across the channel at the floor of the channel, varies from 20 to 260 m (Fig. 17b) but the upper 12 km of the thalweg is wider (~120 m average) than the lower 9 km (~60 m average). The north wall of the canyon is steep (~22°), with low backscatter (−37 dB). Several gullies drain into the north wall of the canyon and one
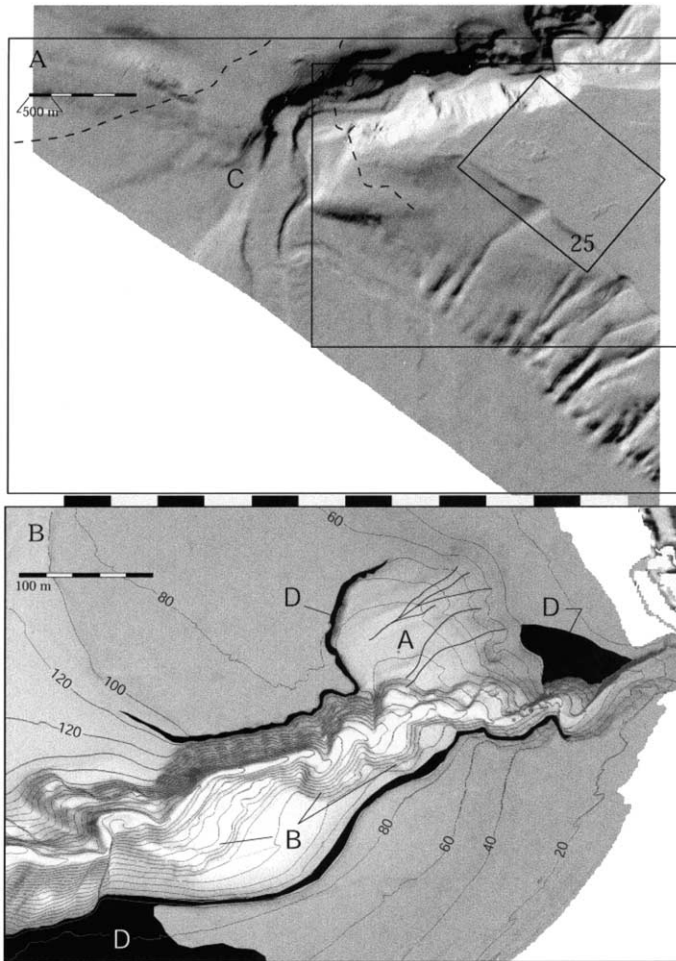
Fig. 13. (a) Plan view of shaded-relief of Redondo Canyon. See Appendix for location. Boundaries for Figs. 13b and 25. (b) Plan view of head of Redondo Canyon. Isobaths in meters. "A" area is large cirque-shaped depression in shelf with channels leading to the canyon. "B" are areas of wall failures. "C" is broad valley (dashed lines) created by low-stand Los Angeles River (see Fig. 14). "D" (black) areas of high backscatter.

large failure is clearly evident along the north wall of the canyon ("a" in Fig. 15). The south wall has a gentle gradient and there is little evidence of mass wasting and no gullies along the top, excluding the canyon head. Santa Monica Canyon trends along the base the Santa Monica plateau to a point 1.15 km from the canyon head, where it continues its southwestern trend out onto the basin floor.

4.3.2. Redondo Canyon

Redondo Canyon heads almost at the coastline in less than 5 m of water. The steep zone of the canyon is 400 m wide at the head and increases to 2500 m wide at
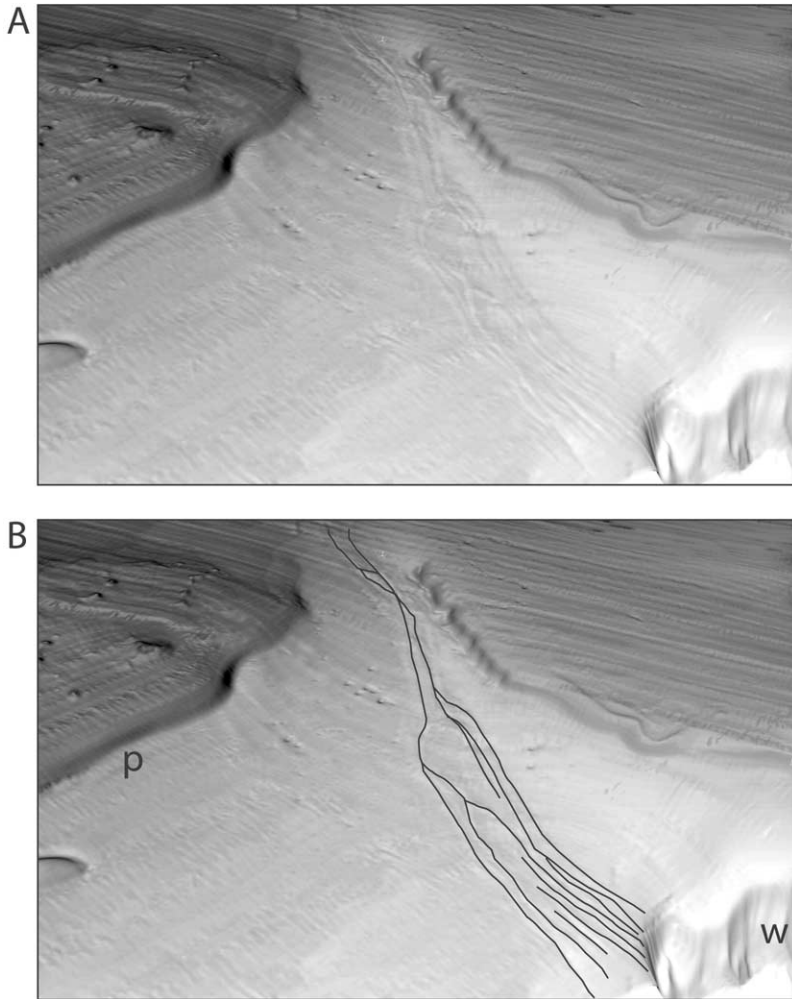
Fig. 14. (a) Oblique view of shaded relief of broad valley created by low-stand Los Angeles River. See Appendix for location. (b) Same view as (a) with distributary channels outlined. "w" is upper north wall of Redondo Canyon, "p" is 20 m high steep zone of Santa Monica plateau. Distance across bottom of image 6 km.

its mouth where it enters Santa Monica basin. Redondo Canyon is composed of three segments; an upper segment 16.6 km long that shows a slightly higher sinuosity index (SI = 0.82); a middle segment about 2.9 km long with only one slight bend; and a lower 3.2 km long segment that is outside the confines of the canyon and parallels the base of the basin slope. The walls of Redondo Canyon are steep (up to 21°) and have a series of basin-slope breaks, although the basin-slope breaks do not correlate across the canyon (Fig. 18). Mass wasting is apparent along both walls and several landslides have blocked the channel in the upper reaches (Fig. 19). The can-

A

1000 m

B

500 m
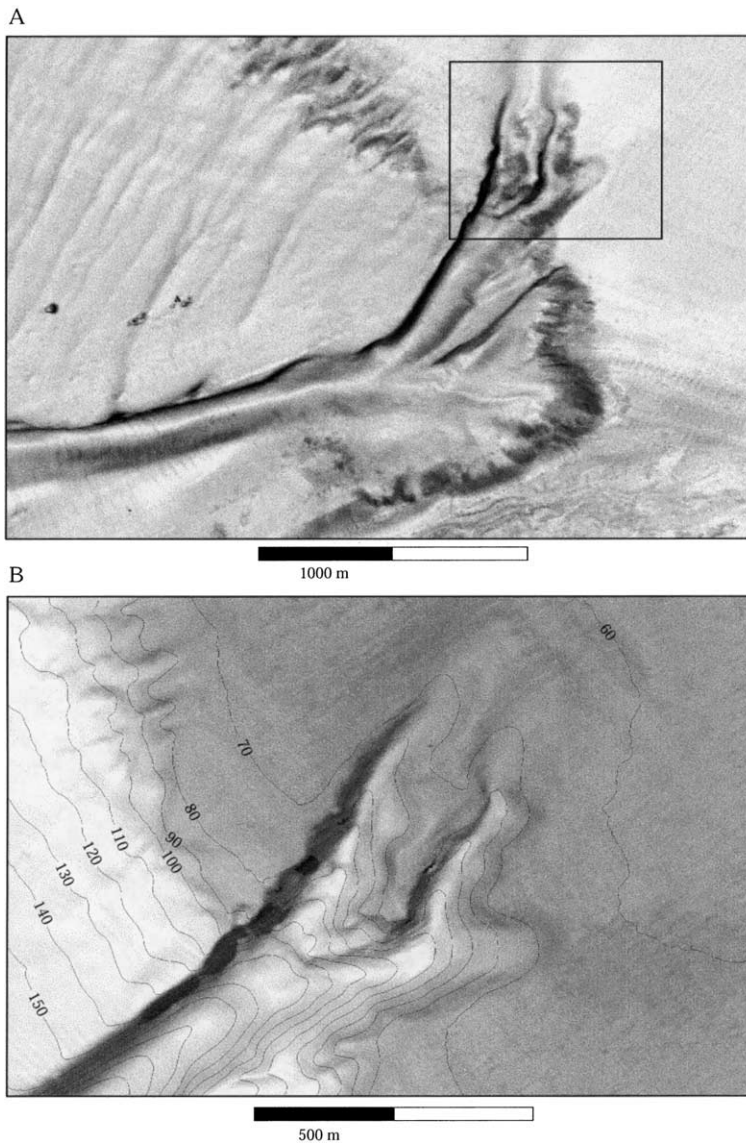
Fig. 15. (a) Plan view of shaded relief of head of Santa Monica Canyon. (b) Close up shaded relief of head of Santa Monica Canyon with contours. See Appendix for location.

yon channel thalweg is 25 m wide at the head and increases to only 95 m wide at the mouth (Fig. 17b). Backscatter of the channel thalweg is relatively high (−27 to −32 dB) compared to the backscatter of the Santa Monica Canyon thalweg.

Redondo Canyon has two canyon channels that continue from the mouth onto the basin floor (a and b on Fig. 20), although Yerkes et al. (1967) report three channels. The most-recently active channel (b on Fig. 20) is located along the south

Fig. 16. Plan view of shaded relief of Santa Monica Canyon. Linear segments of canyon numbered. See text for details. "a" is large failure of north wall. See Appendix for location.
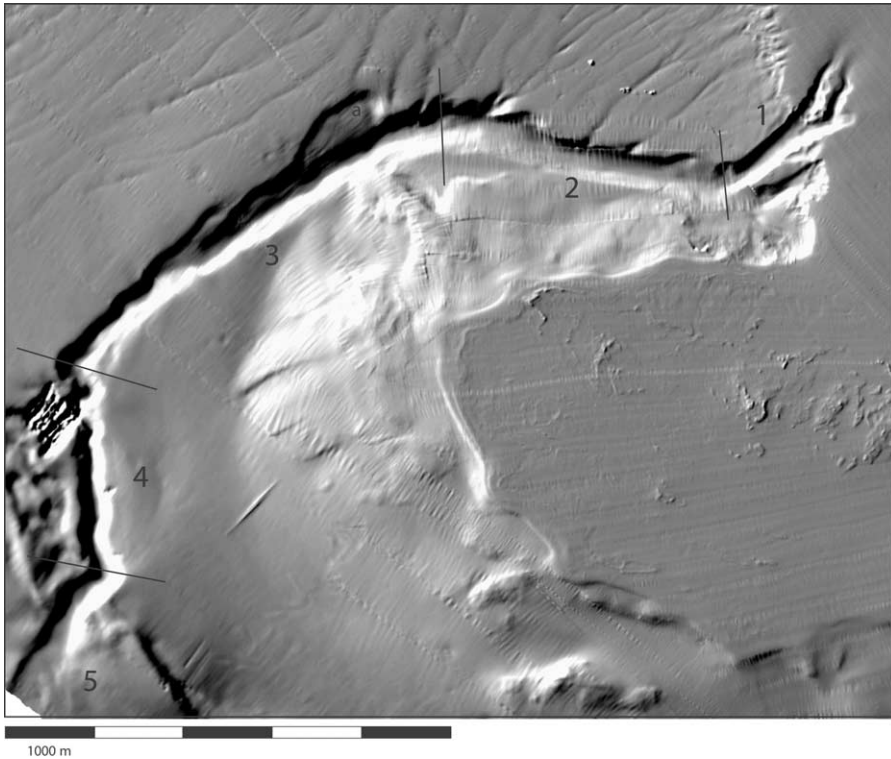
wall of the canyon, is about 100-m wide, and has cut more than 20 m into the basin sediments. This channel has an abrupt 90° left-hand turn about 1000 m after it enters onto the basin, then trends subparallel the base of the basin slope for 5.5 km until it finally loses much of its relief and eventually turns south out onto the basin. The older blocked channel follows the north wall of the canyon and is perched 25-m above the most-recent channel and appears to have been cut off by a landslide just inside the mouth of the canyon.

4.3.3. Dume Canyon

Dume Canyon is located on the northwestern-most corner of the mapped area. The canyon head is a very complex zone with subsidiary slope channels and slump scars (Fig. 21). The canyon head is 1600-m wide and incises across the entire 2.6-km wide shelf. The width of the top of the canyon ranges from 550 to 1600 m and the canyon thalweg width ranges from 20 to 140 m (Fig. 17b). The canyon has incised down about 300 m in the head and the canyon walls are steep (up to 22°). The channel thalweg has a low sinuosity index (SI = 0.73) with only one large (~160°) meander bend. The channel thalweg has relatively high backscatter (−25 dB). Slumping is evident along both walls of the upper canyon and the course of the
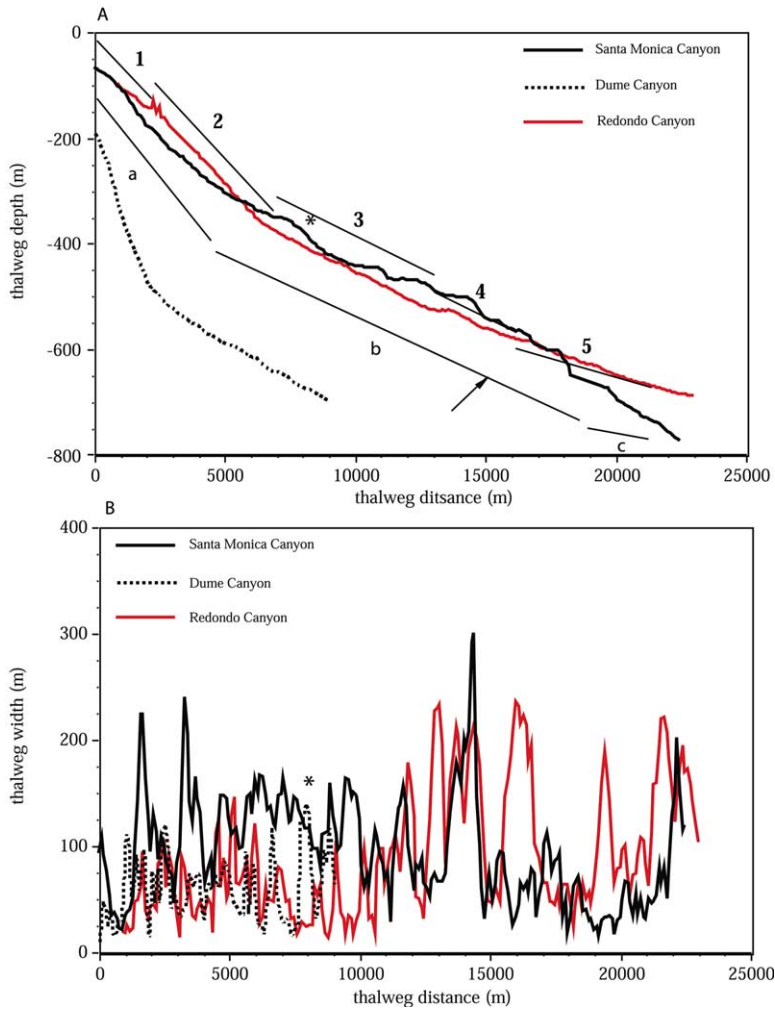
Fig. 17. (a) Plots of thalweg depths (sea level reference) versus thalweg distance for Santa Monica, Dume, and Redondo Canyons. The five segments of Santa Monica Canyon are shown by straight line and numbers. The three segments of Redondo Canyon are shown by straight lines and letters. (b) Plots of thalweg widths versus thalweg distance for Santa Monica, Dume, and Redondo Canyons. The asterisk shows zone of suspected landslides that reduced Santa Monica Canyon thalweg width.

thalweg has been diverted in several areas of the upper canyon by landslides (Fig. 21b).

4.4. Basin slope province

The slope province is defined as the steep (11–14°) region between the shelf and basin but excludes the large apron and the margin of Santa Monica marginal pla-

Fig. 18. Two profiles across Redondo Canyon showing location of "terraces" (short horizontal lines).

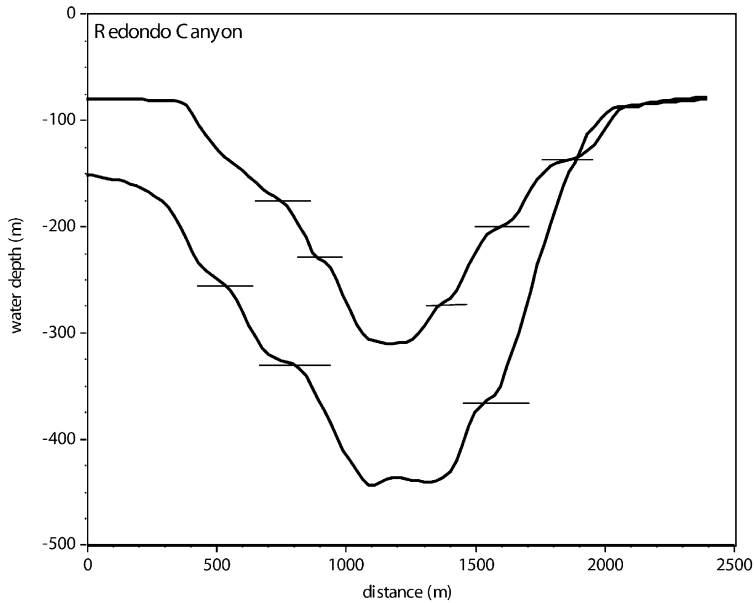teau (Fig. 4). The province occurs in two areas; the Malibu margin and the Palos Verdes margin. The basin slope varies in width from 1.5 km on the Malibu margin to 2.3 km west of the Palos Verdes Peninsula, where the basin slope has been called the San Pedro Escarpment (Shepard & Emery, 1941).

The most distinctive aspect of the basin slope province is the pervasive linear channels, first described by Buffington (1951), that dissect the surface (Fig. 8). The channels typically occur as single, straight to slightly curved, features that range in width from 60 to 300 m across at their upper surfaces with as much as 60 m of vertical relief. Almost all of the channels head at the shelf break and abruptly terminate at the basin floor.

A 25–100 m thick band of relatively high-backscatter (−25 to −27 dB) outcrop is found at the uppermost basin slope adjacent to Dume Canyon at the 95–110-m isobath. The outcrop is continuous to the Santa Monica Plateau where it occurs at the 76-m isobath (Figs. 2 and 3). The thickness of the outcrop is relatively constant along the upper basin slope of the Malibu margin but abruptly increases to about 25 m as the basin slope changes trend from east–west to southeast–northwest.

The lower-most basin slope directly west of Palos Verdes Peninsula has a series of failure scars where the lower basin slope has collapsed or been undercut (Fig. 20). Sections of the lower basin slope up to 100 m high, 2400 m wide, and 200-m thick have spalled away. Debris from the collapses has been deposited on the most proximal basin and forced the Redondo channel to the southwest by as much as 250 m.
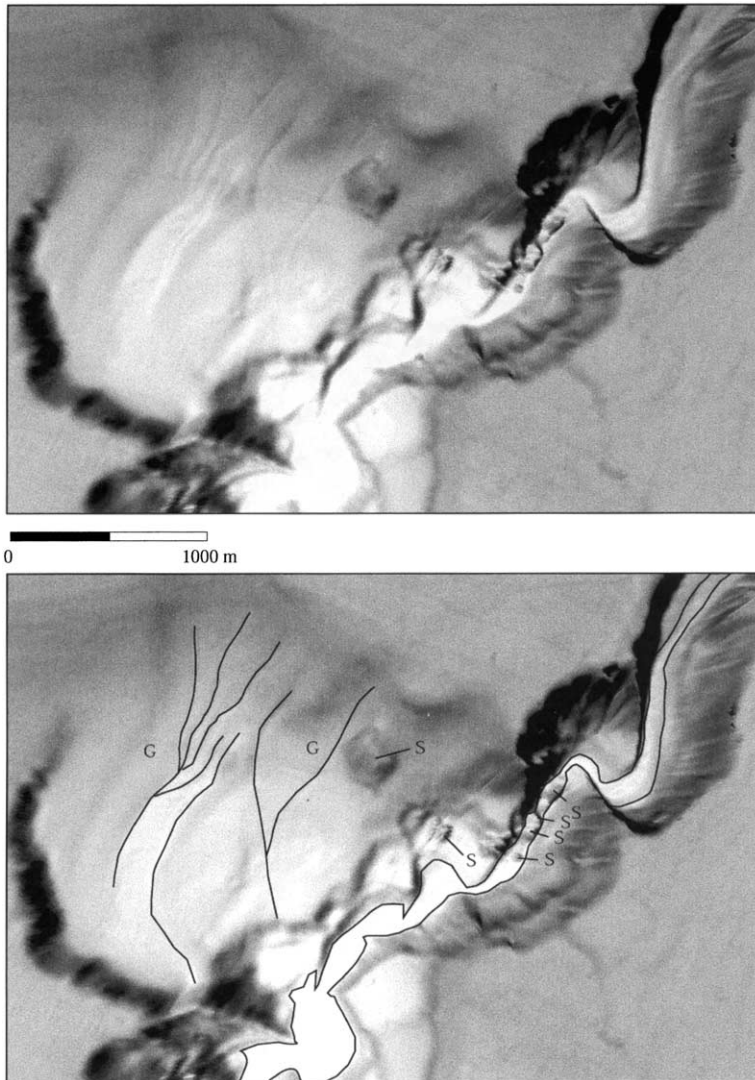
Fig. 19. Plan view of shaded relief of head of Redondo Canyon. Interpretation in lower panel. "S" landslides, "G" gullies in cirque-shaped region of adjacent shelf. See Appendix for location.

4.5. Apron province

The gradient of the basin slope of the Malibu margin gradually decreases toward the east, and becomes a gentle ramp (Fig. 22), called the Santa Monica slope wedge by Haner and Gorsline (1978). Geomorphically, this province is a large, gently sloping, roughly triangular-shaped, apron that extends from the shelf break to the

Fig. 20. (A) Plan view of shaded relief of mouth of Redondo Canyon. (B) Interpretation shown by overlays: (a) blocked outlet channel; (b) active outlet channel; (c) and (d) levees; (e) and (f) failures of north wall; (g) failures of levee c; (h) terrace along north wall; (i) head scarp of basin slope failure; (j) debris pile from basin slope failure that diverted channel. See Appendix for location.
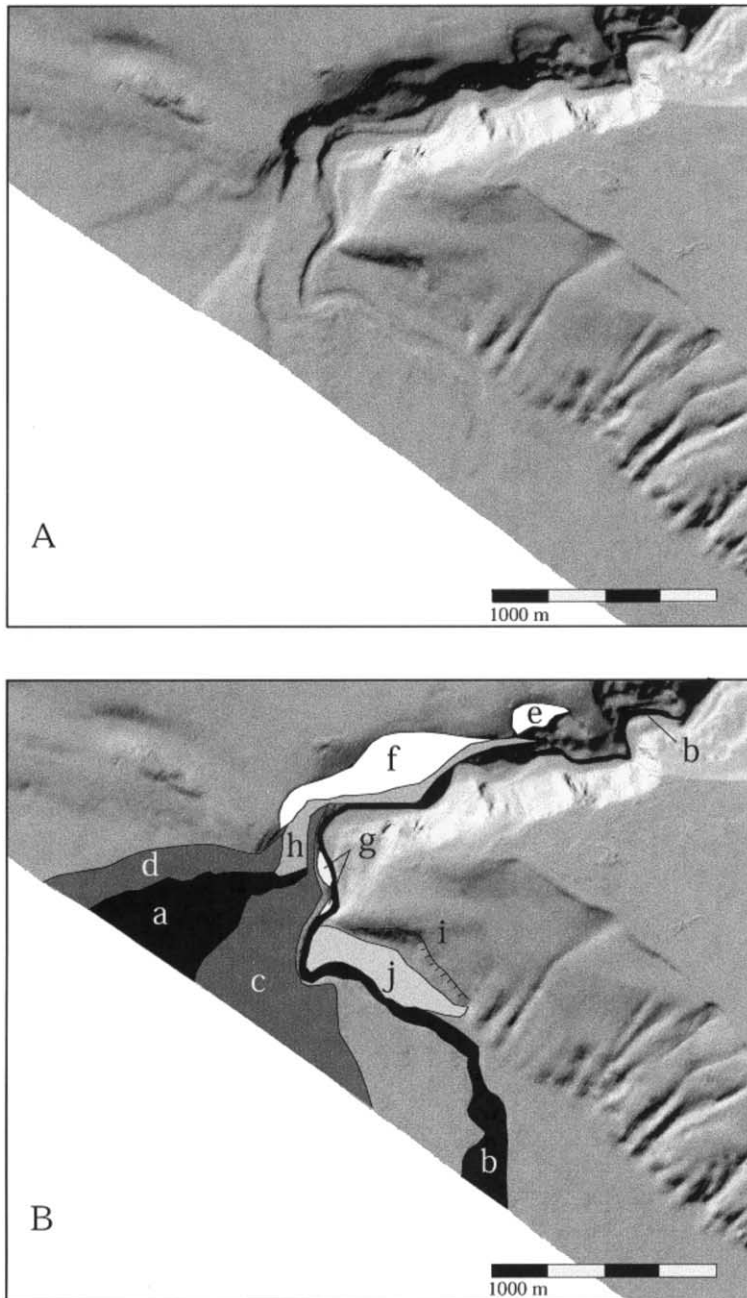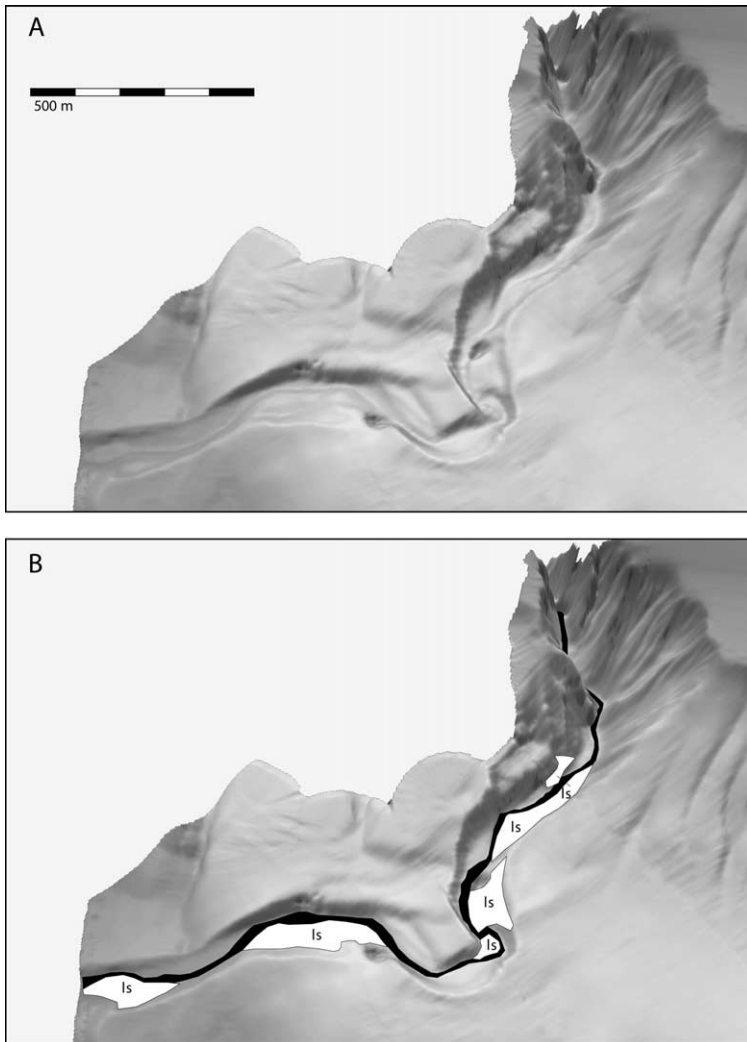
Fig. 21. (a) Oblique view of shaded relief of Dume Canyon. View azimuth 005°. (b) Interpretation showing landslides (white areas labeled "ls") that have diverted Dume channel. See Appendix for location.

distal basin. The apron has dimensions of 20-km east–west, 14-km north–south, and ranges in depth from the 82 m to > 800 m. The apron has a slope that changes from 2° on the shallow end to 1.1° on the deep end (Fig. 23). There is a 20 m high "bulge" of sediment, seen in the profiles across the apron (Fig. 23). The bulge is 3.6 km wide (NW–SE) and 3.2 km long (NE–SW) and occurs between the 180- and 250-m isobaths. The surface of the apron is incised by linear to slightly curving, shallow gullies (Fig. 24), similar in appearance to those described by Field, Gardner, and Prior (1999) from the northern California continental slope. The apron gullies are less than 4 m deep, range from less than 100–200 m wide, and are as much as 6 km long.

Fig. 22. Oblique shaded-relief view of northern Santa Monica Bay. View azimuth 045°. Contour interval 20 m. P1, P2, and P3 locations of depth profiles (Fig. 20). "A" and "B" are outcrops of Pliocene rocks uplifted along extension of San Pedro fault. See Appendix for location.
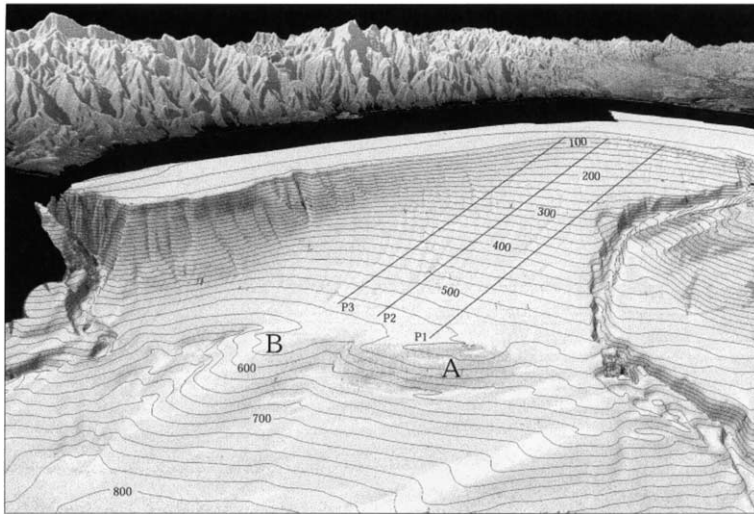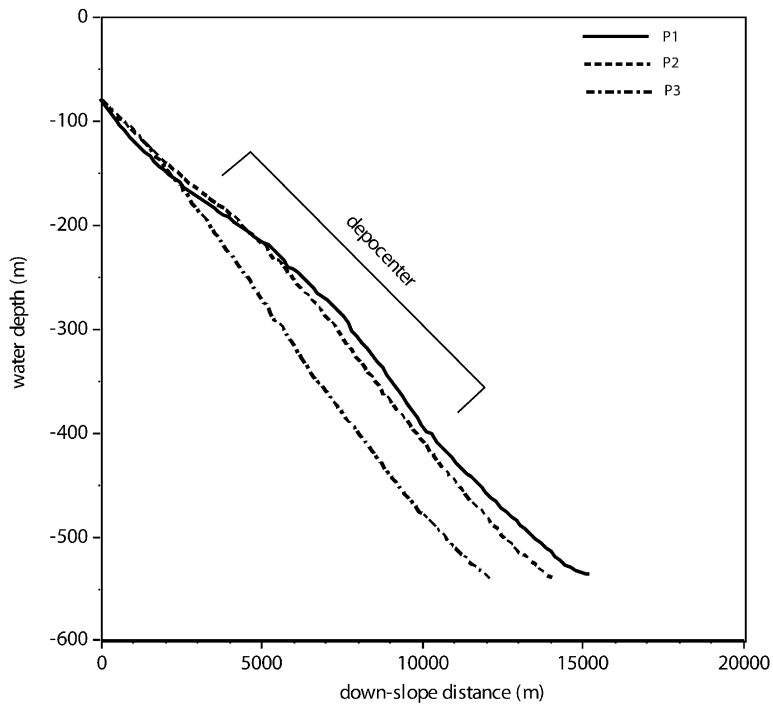

Fig. 23. Depth profiles across apron. See Fig. 22 for location of profiles. Notice the convex shape of profile P1 showing depocenter.

Most of the gullies head at about the 160-m isobath below the zone of slope channels, and many of them have a gentle right-hand curvature and disappear by about the 560-m isobath. Most of the gullies within 6 km of Santa Monica Canyon curve gently to the left and are captured by the canyon.

Two bathymetrically distinct features rise above the surface of the apron near the lower end. One of the features ("A" in Fig. 22) is an isolated 4.5 km long, 1.5 km wide bathymetric high with 65 m of relief. This feature has relatively high back-scatter (−22 dB) suggesting a very different surficial geology from the uniformly low

Fig. 24. Oblique shaded-relief view of eastern Malibu basin slope and northwestern section of proximal apron. See Appendix for location. Lower panel outlines the pattern of gullies. Notice the buried appearance of basin slope channels in apron region. Arrows point to pockmarks.

backscatter (−35 dB) of most of the apron. The other feature ("B" in Fig. 22) is much larger, being 2 km wide, 4.2 km long, up to 50 m high. The backscatter from this second feature is no different from the backscatter of the surrounding 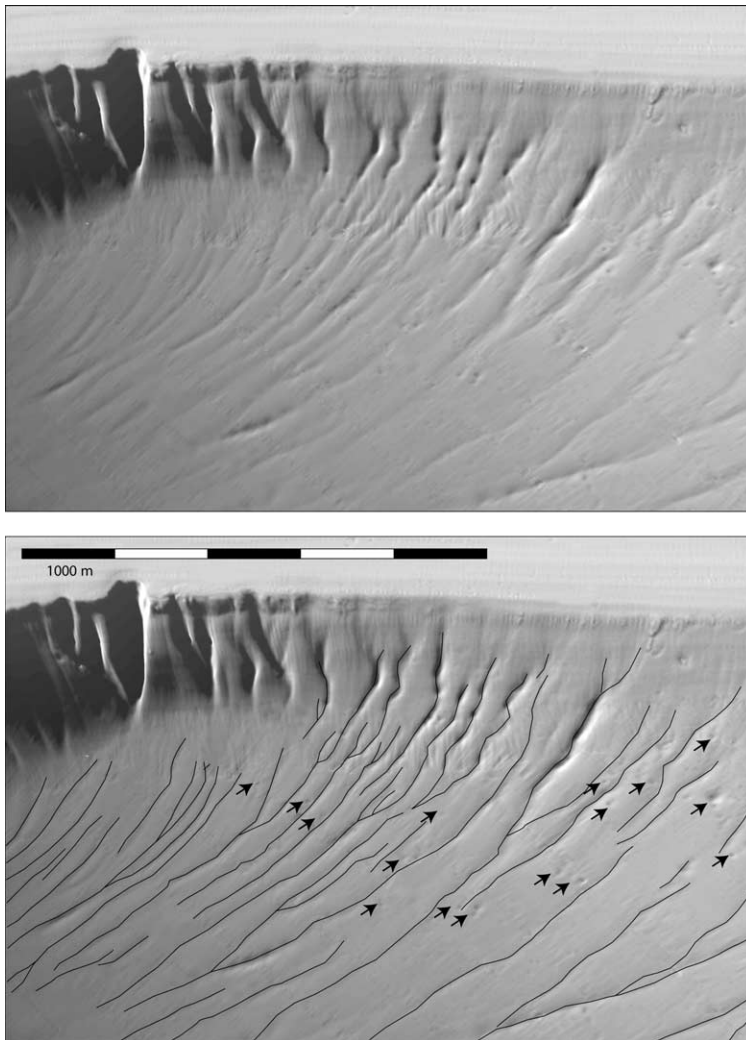sediment apron. Haner and Gorsline (1978) mentioned these features and suggested they represent to toe of a major slide. The detailed bathymetric map does not support this interpretation and the alternative will be presented in the Discussion (Section 5).

A restricted zone of semicircular depressions occurs in the east-central region of the sediment apron (Fig. 24). The depressions range in diameter from 20 to 50 m and from 0.5 to 5 m in depth.

4.6. Basin province

Only a few small areas were mapped of the eastern-most edge of Santa Monica Basin. The basin abruptly begins at the 760-m isobath off the Palos Verdes margin but at the 840-m isobath south of Santa Monica Plateau. The gradients change from 6.5° on the lower slope to <2° on the proximal basin floor. The proximal
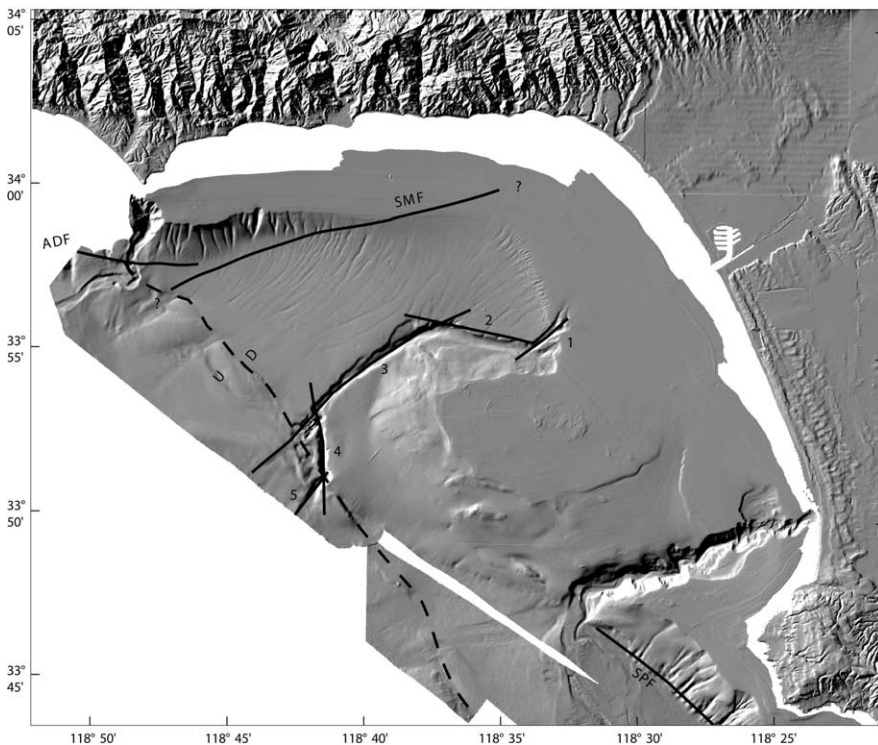

Fig. 25. Trends of known (solid) or inferred (dashed) surface faults in Santa Monica Bay. ADF-Anacapa-Dume fault, SMF-Santa Monica fault; SPF-San Pedro fault; numbered solid lines are linear segments of Santa Monica Canyon (see text for discussion).

basin is cut by several channels (Fig. 2) that are extensions of canyon channels described above. These basin channels have cut as much as 20 m into the basin sediment.

A distinctive north–west lineation extends from a small bathymetric high located off the mouth of Redondo Canyon to the bathymetric highs of the apron province (Fig. 25). This lineation trends ∼25° north of the extension of the San Pedro fault and joins the San Pedro fault at the bathymetric high in the apron province. This lineation is defined by a series of small bisected bathymetric highs found on the proximal basin (Fig. 25). The location and trend of this lineation is similar to an unnamed fault shown on the maps of Junger and Wagner (1977).

5. Discussion

Tectonics, sediment supply, climate, and fluctuations of sea level are the dominant factors that have effected the geomorphology of continental margins (Emery, 1960; Haner & Gorsline, 1978). Santa Monica Bay is actually a microcosm of the inter-action of all these factors.

5.1. Tectonics

The tectonic influence in Santa Monica Bay can be seen in several of the geo-morphic provinces. A series of distinct bathymetric features located toward the sea-ward edge of the mapped area are aligned along a NW–SE trend that suggests the presence of major faults. The two bathymetric highs in the distal area of the apron province are aligned northwest-southeast (Figs. 2 and 22). Haner and Gorsline (1978) mapped these features and suggested they represent a backwall of lower-slope ridges that form a barrier to sediment transport farther down the apron. However, the new bathymetry shows that the two highs have steep northeastern flanks relative to their southwestern flanks, that they are separated by a well-defined channel, and that sediment apparently has bypassed the highs on all sides. Rocks have been sampled at the surface of the southeastern of the two bathymetric highs and were dated as Pliocene in age (Vedder, Greene, Clarke, & Kennedy, 1986). Seismic pro-files (Bohannon, unpublished data) show that a southwest-dipping fault trends along the northeastern edges of the bathymetric highs. The alignment of the eastern flanks of the two bathymetric highs is aligned with the northern arm of the Dume Canyon meander bend (Fig. 25). The meander begins by following a 600 m long, 50–60 m high headland that projects southeast. To the southeast of the two bathymetric highs, the lineation is aligned with the abrupt change in trend of Santa Monica Canyon (segments 4–5). This trend continues to the southeast to align with isolated bathymetric highs just seaward of the lower slope of the Santa Monica plateau.

The segmentation of Santa Monica Canyon into five linear reaches suggests the canyon has followed a conjugate fault system within a complex stress system apparently unrelated to that which created the San Pedro fault. The linear trends of the Santa Monica Canyon segments and the lack of a sinuous channel thalweg are

additional indicators of fault control for the canyon. Segments 1, 3, and 5 of Santa Monica Canyon are roughly parallel to the Anacapa-Dume and Santa Monica faults (Fig. 25) that trends east-northeast from Dume Canyon along the adjacent basin slope and cuts across the shelf (Haner & Gorsline, 1978; Haukkson & Saldivar, 1989; Junger & Wagner, 1977). Although there is no geomorphic evidence for the Santa Monica fault, Haner and Gorsline (1978) cite seismic-reflection profiles that define the fault.

Yerkes et al. (1967) and Haner and Gorsline (1978) suggest Redondo Canyon follows a fault trace, at least through the lower half of its reach. Yerkes et al. (1967) describe the channel as unusually straight with a V-shaped profile. However, the multibeam bathymetry suggests that the canyon trend is more complicated than that of simply following a fault trace. The sinuous channel thalweg wanders over a large area, suggesting this part of the canyon trend has been shaped by canyon-wall failures. Although the lower half of the canyon reach has fewer thalweg turns than the upper half, the channel continues to wander over an area wider than 100 m. Seismic-reflection profiles published by Yerkes et al. (1967) show acoustic-reflector continuity across either side of the lower portion of the canyon but clearly suggest a fault that juxtaposes Pliocene and Miocene sediments that strikes east–west at a high angle across the canyon about midway along its reach.

The basin slope along the southwest Palos Verdes margin shows signs of collapse. Seismic profiles over this basin slope (Bohannon & Gardner, in press) show that the basin slope parallels the descending limb of an anticline. The collapse could have been caused by earthquake activity of the San Pedro fault. However, an alternate explanation is that the lower basin slope was undercut by Redondo channel where it flows out of Redondo Canyon.

5.2. Sedimentation

Sedimentation has dominated the processes in the area between Santa Monica plateau and the Malibu margin. The apron province is most likely the result of low-stand depositional episodes related to the ancestral Los Angeles River. During eustatic low stands of sea level, the Los Angeles River traversed across the exposed shelf and reached the low-stand coast just north of Santa Monica plateau at about the present 120-m isobath (Fairbanks, 1989). No buried channels have been found on the shelf, suggesting the ancestral Los Angeles River traversed the shelf as a dispersed, distributary with no appreciable incision. The shelf break is almost completely buried in the area where it bends from east–west to north–south (Figs. 2 and 25), suggesting this area was a major depocenter during lows stands. The multi-headed incision of the shelf by the Santa Monica Canyon suggests that during some of the low-stand conditions the mouth of the low-stand Los Angeles River was located directly in line with the canyon head (Fig. 15). And, during other low stands, the mouth of the river migrated farther south to the broad valley that leads directly into Redondo Canyon (Fig. 14). The drainage basin of the Los Angeles River encompasses the tectonically rising mountains surrounding the Los Angeles basin, which have provided a ready supply of sediment to the river.

5.3. Climate and sea level

The variations in sediment supply in Santa Monica Bay are tightly coupled with climate and eustatic sea levels. During the Holocene, prior to its diversion in the 19th century, the mouth of the Los Angeles River was located just south of the city of Santa Monica. Pollen assemblages suggest the Holocene climate was mostly arid and the Pleistocene climate was moist (Heusser, 1995) when eustatic sea level was 120 ± 5 m lower than today (Fairbanks, 1989; Pillans, Chappell, & Nash, 1998). The higher glacial precipitation would have supplied a large volume of sediment to the mouth of the river and the apron province is the low-stand wedge (Posamentier & Vail, 1988) that reflects this increase. The apron has a convex shape that rises 25 m above the flat surface (Fig. 23). The axis of the depocenter is 7-km downslope from the shelf break. The lack of backscatter variability of the apron suggests the upper few tens of centimeters is composed of a relatively consistent sediment facies. The small-scale gullies that incise the apron province may be the infilled remnants of incised gullies that characterize the geometry during a falling sea level (Posamentier & Vail, 1988). When the mouth of the Los Angeles River was north of Santa Monica Canyon, sediment was supplied to, and partially buried, the shelf break. At other low-stand conditions, the mouth of the river connected directly with the heads of Santa Monica Canyon. At least once during a low stand, the mouth of the Los Angeles River jumped more than 5 km to the south to the southeastern edge of Santa Monica plateau where it developed a distributary system that incised a broad valley sloping to the north wall of Redondo Canyon.

The relatively large diameter (20–50 m) depressions found in the apron province are similar in size to pockmarks associated with expulsion of gas (Hovland, 1981; Yun, Orange, & Field, 1999). The pockmarks occur in the area where the apron province has a pronounced convex bulge, suggesting deposition of organic-carbon-rich sediments by the lowstand Los Angeles River. Most of the pockmarks appear relatively fresh suggesting recent venting.

Redondo Canyon heads less than 100 m from the present shoreline so that fluctuations of eustatic sea level would have only a small effect on the transport of sediment to the canyon head. Drilling located a buried fluvial late Pleistocene channel lying onshore directly opposite the head of the canyon (Yerkes et al., 1967). Although Crowell (1952) speculated that no paleo-river flowed into the canyon head, Yerkes et al. (1967) suggest that the canyon head may be related to what has been called the Gardena River. The presence of this infilled channel suggests the canyon and the present coastal area were downcut during low-stand conditions and the canyon filled during the last marine transgression. The multibeam data show that the thalweg of the canyon is presently blocked by several massive landslides (Fig. 19).

Dume Canyon also heads very close to shore and Dume (Zuma) Creek is closely adjacent on land (Crowell, 1952). Like Redondo Canyon, fluctuations in sea level would have a small effect on sediment sources to the canyon head. Although there are numerous landslides in the head of the canyon, none appear to presently block the thalweg; consequently, the system may still be active. Certainly the high relief of

the Malibu margin (∼800 m), coupled with the narrow shelf and the across-shelf incision would argue for present-day active canyon transport.

A band of high backscatter (−20 dB) just barely imaged along the inner shelf close to the mouth of the former Los Angeles River may represent a high-stand delta formed by the Los Angeles River before it was diverted in the nineteenth century.

The top surface of Santa Monica plateau has been a sediment-starved environment for some time. The flat surface is a truncation surface most likely created by the successive sea-level transgressions during the Quaternary. The only significant sediment on the plateau has been generated from the locally more resistant rock outcrops. The depth of the plateau surface lies just above the 120±5 m maximum eustatic sea level lowering during the last glacial maximum (Fairbanks, 1989; Pillans et al., 1998), indicating that the surface of Santa Monica plateau has been exposed and transgressed over numerous times. Subaerial and wave-base erosion have planed the plateau surface down to its present relief, leaving the more erosion-resistant rock projecting above the surface. The plateau has not been a significant depocenter for sediment, probably because the bordering submarine canyons have intercepted the supply of sediment before it could get to the plateau.

6. Conclusions

The 1996 USGS multibeam survey is the first substantive remapping of the entire Santa Monica Bay since the original mapping by Shepard and Emery (1941). The 1941 map defines the broad outlines of the bathymetric features but lacks detail and is too generalized to define many of the important characteristics of the features. The multibeam bathymetry represents a quantitative three-dimensional dataset that allows the accurate description of features as small as a few meters in horizontal dimensions by less than 1 m of relief. In addition, the multibeam data also provides quantitative acoustic backscatter, providing important insights into the surficial geology of the area. Once combined with ground truth, the backscatter becomes critical in mapping the surficial geology (Dartnell & Gardner, in preparation). Together, these datasets have produced an unprecedented view of the physiography of Santa Monica Bay.

Images of shaded relief and backscatter of Santa Monica Bay can be downloaded from the web at http://walrus.wr.usgs.gov/pacmaps. The digital data are available on CD-ROM (Dartnell & Gardner, 1999) and it, as well as paper copies of the shaded-relief and acoustic-backscatter maps (Gardner, Dartnell, Mayer, & Hughes Clarke, 1999; Gardner, Dartnell, Stone, Mayer, & Hughes Clarke, 2002), can be obtained from the U.S. Geological Survey, Box 25046, Denver, CO 80225-0046.

The use of trade, product, or firm names in this report is for descriptive purposes only and does not imply endorsement by the US Government.

Appendix. Outlines and view directions of figures in manuscript
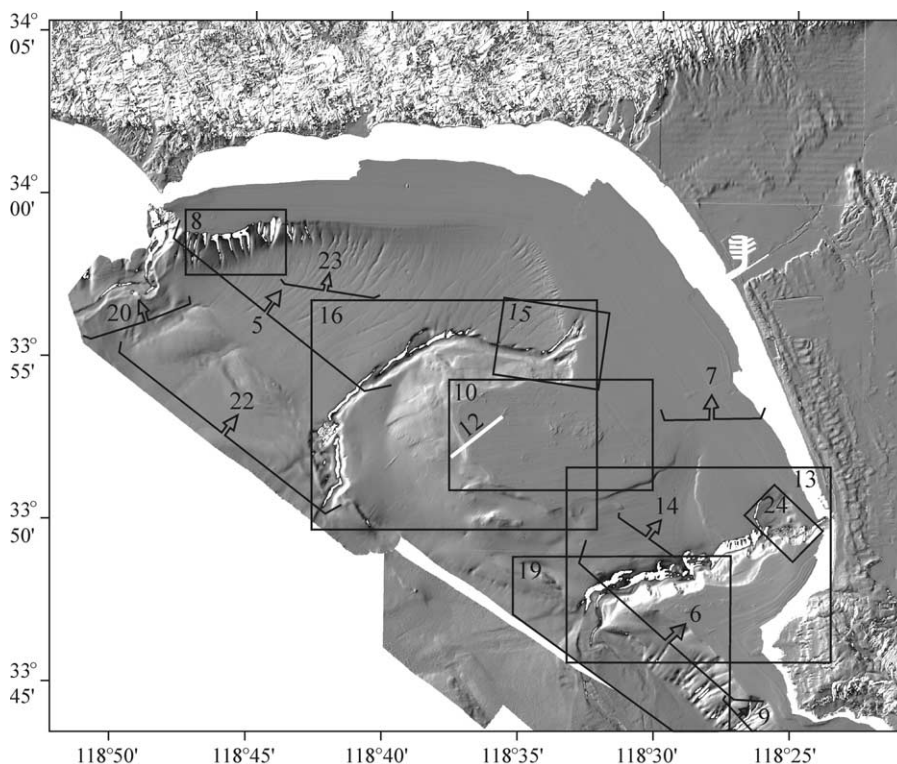
References

Bohannon, R. G., & Gardner, J. V. (2003). Submarine landslides of San Pedro Sea Valley, southwest of Long Beach, California. *Marine Geology*, in press.

Buffington, E. C. (1951). Gullied submarine slopes off southern California. *Geological Society of American Bulletin*, *62*, 1497.

Crowell, J. C. (1952). Submarine canyons bordering central and southern California. *Journal of Geology*, *60*, 58–83.

Dartnell, P. (2000). *Applying remote sensing techniques to map seafloor geology/habitat relationships*. MA thesis, San Francisco State University.

Dartnell, P., & Gardner, J. V. (1999). *Sea-floor images and data from multibeam surveys in San Francisco Bay, southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada*. US Geological Survey Digital Data Series DDS-55, version 1.0 (CD-ROM).

Dartnell, P., & Gardner, J. V. (in preparation). Predicting seafloor composition from multibeam bathymetry and backscatter data.

Emery, K. O. (1960). *The sea off southern California*. New York: John Wiley & Sons.

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. *Nature*, *342*, 637–642.

Field, M. E., Gardner, J. V., & Prior, D. P. (1999). Geometry and significance of stacked gullies on the northern California slope. *Marine Geology*, *154*, 271–286.

Gardner, J. V., Field, M. E., Lee, H. J., Edwards, B. E., Masson, D. G., Kenyon, N., & Kidd, R. B. (1991). 6.5 kHz backscatter; what are we really imaging? *Journal of Geophysical Research*, *96*, 5955–5974.

Gardner, J. V., Dartnell, P., Mayer, L. A., & Hughes Clarke, J. E. (1999). *Shaded-relief bathymetric and backscatter maps of Santa Monica margin, California*. US Geological Survey Geological Investigations Series Map I-2648, two sheets, scale 1:75,000.

Gardner, J. V., Dartnell, P., Stone, J. C., Mayer, L. A., & Hughes Clarke, J. E. (2002). Bathymetry and selective perspective views of offshore greater Los Angeles, California. *U.S. Geological Survey Water Resources Investigations Report 02-2146*.

Haner, B. E., & Gorsline, D. S. (1978). *Marine Geology*, *28*, 77–87.

Hauksson, E., & Saldivar, G. V. (1989). Seismicity and active compressional tectonics in Santa Monica Bay, Southern California. *Journal of Geophysical Research*, *94*, 9591–9606.

Heusser, L. E. (1995). Pollen stratigraphy and paleoecologic interpretation of the 160-ky record from Santa Barbara Basin, Hole 893A. In J. P. Kennett, J. G. Baldauf, & M. Lyle (Eds.), *Proceedings of the Ocean Drilling Program,* Scientific Results, vol. 146, Part 2, (pp. 265–279).

Hovland, M. (1981). Characteristics of pockmarks in the Norwegian Trench. *Marine Geology*, *39*, 103–117.

Hughes Clarke, J. E., Mayer, L. A., & 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*, *18*, 607–629.

Junger, A., & Wagner, H. C. (1977). *Geology of the Santa Monica and San Pedro basins, California continental borderland*. US Geological Survey Misc. Field Study, Map MF-820, five sheets, one pamphlet, scale 1:250,000.

Mayer, L. A., Hughes Clarke, J. E., & Wells, D., HYDRO-92 Team (1993). A multifaceted acoustic ground-truthing experiment in the Bay of Fundy. *Proceedings of the Institute of Acoustics*, *15*(2), 203–219.

Mayer, L. A., Hughes Clarke, J. E., & Dijkstra, S. (1997). Multibeam sonar: Potential applications for fisheries research. In G. W. Boehlert, & J. D. Schumacher (Eds.), *Changing oceans and changing fisheries: environmental data for fisheries research and management* (pp. 79–92). NOAA-TM-NMFS-SWFSC-239: NOAA Tech. Memo.

Mitchell, N. C. (1993). Attempts to determine acoustic attenuation in sediment drapes overlying rocky surfaces from sidescan-sonar imagery. *American Association of Petroleum Geologists Bulletin*, *62*, 327–333.

Nardin, T. R., & Henyey, T. L. (1978). Pliocene-Pleistocene diastrophism of Santa Monica and San Pedro shelves, California continental borderland. *American Association of Petroleum Geologists Bulletin*, *62*, 247–272.

Pillans, B., Chappell, J., & Naish, T. R. (1998). A review of the Milankovitch climatic beat: template for Plio-Pleistocene sea-level changes and sequence stratigraphy. *Sedimentary Geology*, *122*, 5–21.

Posamentier, H. W., & Vail, P. R. (1988). Eustatic controls on clastic deposition II-Sequence and systems tract models. *Society of Economic Paleontologists and Mineralogists Special Publication*, *42*, 39–45.

Shepard, F. P., & Emery, K. O. (1941). Submarine topography off the California coast: canyons and tectonic interpretation. *Geological Society of America Special Paper*, *31*, 1941.

Terry, R. D., & Stevenson, R. E. (1957). Microrelief of the Santa Monica Shelf, California. *Geological Society of America Bulletin*, *68*, 125–128.

Vedder, J. G., Greene, H. G., Clarke, S. H., & Kennedy, M. P. (1986) *Geologic map of the mid-southern California continental margin*. California continental margin geologic map series, Map. No. 2A, scale 1:250,000.

Yerkes, R. F., Gorsline, D. S., & Ruysnak, G. A. (1967). US Geological Survey Prof. Paper 575-C, pp. C97–105.

Yun, J. W., Orange, D. L., & Field, M. E. (1999). Subsurface gas offshore of northern California and its link to submarine geomorphology. *Marine Geology*, *154*, 357–368.