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Submarine canyon and fan systems of the California Continental Borderland

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ABSTRACT

Late Quaternary turbidite and related gravity-flow deposits have accumulated in basins of the California Borderland under a variety of conditions of sediment supply and sea-level stand. The northern basins (Santa Barbara, Santa Monica, and San Pedro) are closed and thus trap virtually all sediment supplied through submarine canyons and smaller gulley systems along the basin margins. The southern basins (Gulf of Santa Catalina and San Diego Trough) are open, and, under some conditions, turbidity currents flow from one basin to another. Seismic-reflection profiles at a variety of resolutions are used to determine the distribution of late Quaternary turbidites. Patterns of turbidite-dominated deposition during lowstand conditions of oxygen isotope stages 2 and 6 are similar within each of the basins. Chronology is provided by radiocarbon dating of sediment from two Ocean Drilling Program sites, the Mohole test-drill site, and large numbers of piston cores.

High-resolution, seismic-stratigraphic frameworks developed for Santa Monica Basin and the open southern basins show rapid lateral shifts in sediment accumulation on scales that range from individual lobe elements to entire fan complexes. More than half of the submarine fans in the Borderland remain active at any given position of

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relative sea level. Where the continental shelf is narrow, canyons are able to cut headward during sea-level transgression and maintain sediment supply to the basins from rivers and longshore currents during highstands. Rivers with high bedload discharge transfer sediment to submarine fans during both highstand and lowstand conditions.

INTRODUCTION

The California Borderland provides an ideal morphological and geological setting to study source-to-sink sedimentation processes during the late Quaternary. This chapter describes and interprets late Quaternary deposits in the "sinks," a series of six inner basins that border the generally narrow continental shelf between Point Conception and San Diego, California (Fig. 1). The active tectonism in and around the Borderland basins results in abundant sediment supply to the coastal areas even during sea-level highstands. For all but one of the basins, turbidite sediment funneled to deeper water through submarine canyons forms the bulk of the basin fills. Sea-level changes control the distribution of turbidite sedimentation within the offshore basins by influencing the supply of sediment to submarine canyons, many of which remain (or become more) active during sea-level rise. As a result, half of the submarine canyons in the Borderland remain active during the late Holocene highstand (Romans et al., 2009).

From northwest to southeast, the basins progressively become deeper, with lower sills. The three northern basins—Santa Barbara, Santa Monica, and San Pedro (Fig. 1)—are closed depressions that trap all turbidity-current input. In the three southern basins—western and eastern Gulf of Santa Catalina and San Diego Trough—the sills have been overtopped as the basin filled, resulting in sediment transport to an adjacent, more seaward basin. The western Gulf of Santa Catalina now loses sediment to the Catalina Basin west of Santa Catalina Island. The eastern Gulf of Santa Catalina feeds sediment to the northern San Diego Trough, which in turn periodically loses sediment to San Clemente Basin southwest of San Diego.

Tectonic Setting

The turbidite systems of the inner basins of the Borderland are fed from submarine canyons that cross active faults along the basin slopes and consist of submarine fans that lead in most cases to ponded basin-plain deposits. In many cases, the fans themselves are also built in actively deforming areas. The structure and tectonics of the study area are presented in detail in Section 4 of this volume. Here, only a summary is presented of the influence of tectonism on basin setting and the allogenic effects of faulting and uplift on turbidite deposition during the latest Quaternary.

Santa Barbara Basin and the adjacent northern margin of Santa Monica Basin are deformed by folding and faulting related to north-south crustal shortening that continues in the actively deforming Transverse Ranges immediately to the north. A regional transition to northwest-southeast, strike-slip motion occurs within Santa Monica Basin, and basins farther to the south are bounded by oblique-slip faults in a generally transpressive tectonic regime (Vedder, 1987; Crouch and Suppe, 1993, Legg and Nicholson, 1993; Klitgord and Brocher, 1996). Strata older than late Quaternary along the margins of the basins generally show progressively increasing deformation with subbottom depth. Uplifted equivalents of the latest Quaternary turbidite deposits are known from outcrops on land and from wells in the Los Angeles Basin (e.g., Wright, 1991; Normark and Piper, 1998, Fisher et al., 2003, 2004a, 2004b). This rapid uplift of the Transverse Ranges and onshore areas farther south results in relatively high sedimentation rates in the modern offshore basins.

Chronostratigraphy

The timing of active turbidite deposition in the latest Pleistocene and Holocene is based on more than 40 relatively short piston cores (Normark et al., this volume, Chapter 2.6). Two of the closed basins were additionally cored by the Ocean Drilling Program (ODP) and provide a longer chronostratigraphic record. Site 893 in Santa Barbara Basin was cored to 200 m below seafloor (mbsf) reaching sediment ca. 160 ka (Shorebased Scientific Party, 1994). Site 1015 in Santa Monica Basin was cored to 150 mbsf reaching sediment ca. 60 ka (Shipboard Scientific Party, 1997). This long chronology provides additional context for interpretation of turbidity-current transport and deposition in the open basins farther south, where the only long chronologic control is provided by the Mohole drilling project of the 1960s (Inman and Goldberg, 1963).

Purpose

This review of the inner basins of the California Borderland in part updates the overview of Moore (1969), who also used seismic-reflection profiling to understand the nature and history of Quaternary basin sedimentation as part of his structural studies. Because of the availability of high-resolution reflection profiles, it is now possible to closely examine the effects of sea-level change on latest Quaternary deposition. Two of the basins, Santa Monica Basin and San Diego Trough, will be discussed in more detail than the others in this review. Both basins are fed by more than one submarine canyon that has remained active at highstand. In addition, there is sufficient high-resolution, seismic-reflection data from both basins to resolve autogenic shifts in channel and lobe deposits during sea-level rise following the Last Glacial Maximum (LGM). Santa Monica Basin is closed, whereas San Diego Trough is open to the south and periodically helps feed Navy Fan in South San Clemente Basin (Normark et al., 1979),

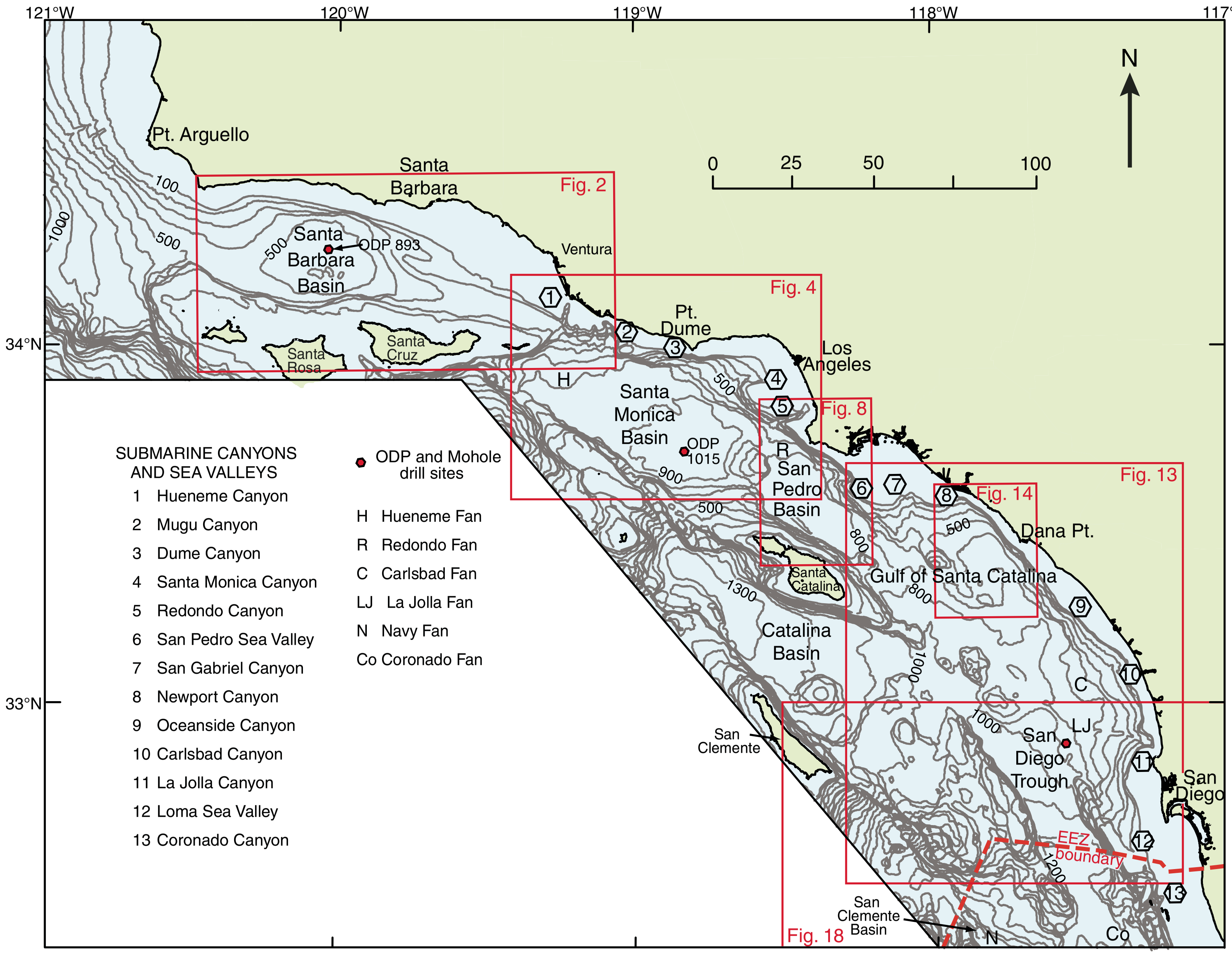


Figure 1. Map showing Southern California Borderland area from Point Conception to the U.S.–Mexican Exclusive Economic Zone (EEZ) boundary. Red rectangles show area of map figures used for discussion of specific basins. Names of the major inner basins, submarine canyons, and associated submarine fans of the Borderland are shown along with the location of three sites of scientific drill cores. Contour interval is 100 m and based on Divins and Metzger (2003; see also National Oceanic and Atmospheric Administration, 1998). ODP—Ocean Drilling Program.

thus allowing for comparison in the growth patterns of submarine fans in these two basins.

Methods

This review of late Quaternary sedimentation on turbidite fans of the inner Borderland is based primarily on new seismic-reflection data and radiocarbon dating of sediment core samples, both of which were obtained to evaluate earthquake and landslide hazards. Sedimentation rates derived from the radiocarbon dating of cores (using calibrated ages) are presented in Normark et al. (this volume, Chapter 2.6), and details of the radiocarbon dating are given in Normark and McGann (2004) and Chapter 2.6. The sedimentation rate data can be combined with interpretation of high-resolution acoustic profiles to understand both the temporal and spatial deposition within the basins for the past 30 ka, and by extrapolation, locally back to ca. 200 ka.

For this study, most high-resolution, seismic-reflection data were obtained using a Huntec DTS™ boomer system. This system is towed ~150 m below the sea surface, and data quality is improved with heave and depth compensation for the tow vehicle. The signals, which were generated at 500 Joules output energy, were received on a 15-ft-long, 10-element, oil-filled streamer (Benthos MESH 15/10P) towed behind the fish; the signals were filtered at 0.5–10 kHz with spreading-loss gain recovery. The advantage of the deep-tow boomer signal is a broad frequency bandwidth (up to 6 kHz), which yields an optimal vertical resolution of ~0.25 m. Signal levels are generally sufficient to yield acoustic imaging up to 100 m below the seafloor in nonsandy sections.

Interpretation of the turbidite elements within the basins was also based on high-resolution (i.e., two-second subbottom records), multichannel seismic (MCS) reflection data that provide information on the older (>30 ka) successions and on the effects of tectonism within the basin area (see Section 5 of this volume). Most data were collected using a 575 cm^3, double-chamber, gas-injection air gun and a 24-channel streamer with 10-m-long groups. The data were migrated at 85% of stacking velocity with the application of a 500-ms automatic gain control (AGC). These data were augmented by review of industry and U.S. Geological Survey (USGS) deep-penetration multichannel data.

SUBMARINE CANYONS, FANS, AND BASIN SEDIMENTATION

Santa Barbara Basin

The Santa Barbara Basin is distinct from the other inner basins because it lacks morphology resulting from turbidite fan deposition during the late Quaternary (Fig. 2). Many small channels extend from the shelf edge on the northwestern basin margin toward the center of the basin, but the typical mounded seafloor expression of turbidite fan lobes is absent. These channels are possibly related to a relict submarine turbidite system called the Conception Fan (CF in Fig. 2), which is thought to have been abandoned ca. 500 ka as a result of uplift and deformation in the Point Conception area, shifting sediment transport to the west (Kraemer, 1987; Fischer et al., 1989; Marsaglia et al., 1995). These channels might have remained active in feeding silt and mud to the deep basin, but Marsaglia et al. (1995) do not think that the sand beds recovered at ODP Site 893 came from this northwestern source. They demonstrate that the provenance of the late Pleistocene sand at Site 893 is from the eastern end of the basin, e.g., the Santa Clara River.

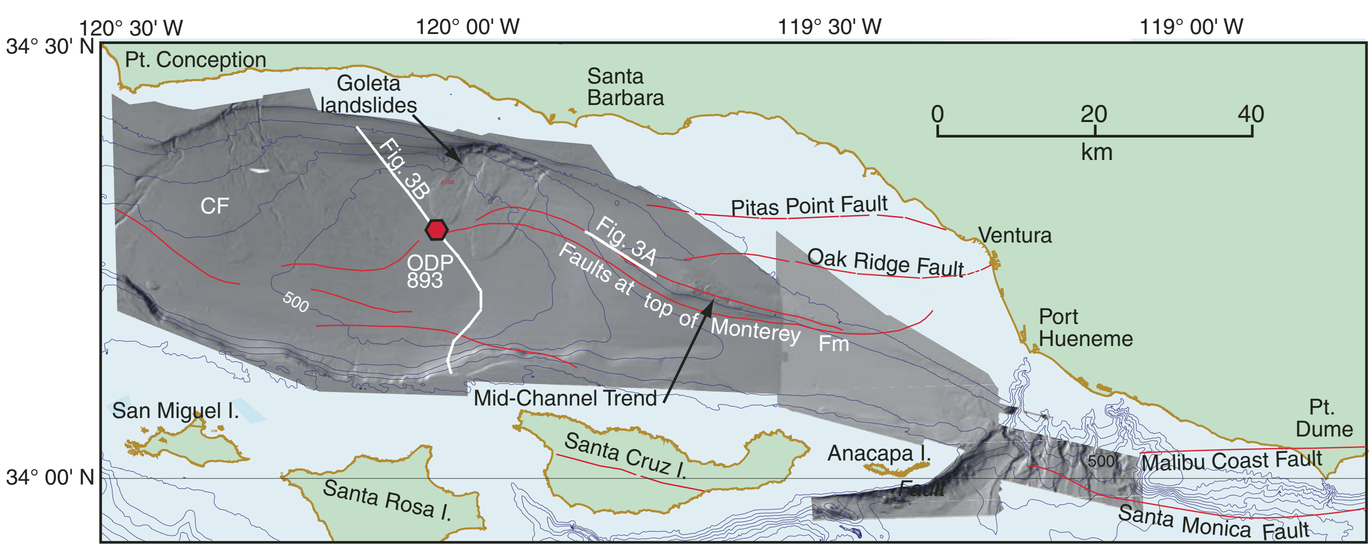


Figure 2. Shaded relief image of Santa Barbara Basin showing Goleta landslide complex and the Mid-Channel Trend; multibeam bathymetry adapted from Monterey Bay Aquarium Research Institute (MBARI, 2001). Faults (red lines) simplified from Fisher et al. (this volume, Chapter 4.4). Profile locations for Figures 3A and 3B and Ocean Drilling Program (ODP) Site 893 are shown. CF—Conception Fan.

Seismic-reflection profiles across the center of the basin show little evidence for submarine fan development in the late Pleistocene. Multichannel seismic-reflection line L490–107 (Fig. 3B) trends southeast between the area of channels and the large submarine slide deposits, passing through ODP Site 893. The upper half-kilometer of basin fill consists of flat-lying reflections that lap onto the basin margins. Acoustic character that might represent sandy submarine fan deposits is found in intervals of more mounded deposition below 800 mbsf (~1 s two-way travel time [TWTT]) near the base of the northern margin of the basin and indistinct lenses of less coherent reflections at 400–900 mbsf (0.5–1.1 s TWTT) subbottom at the southern margin of the basin (Fig. 3B; Normark et al., 2006a). Linear extrapolation of sedimentation rates at ODP Site 893 and the projected results from the Nicholson et al. (2006) study suggest that the shallowest probable sandy turbidite sequence, e.g., the acoustically incoherent lens at the southern margin of the basin, corresponds to oxygen isotope stage (OIS) 10 (ca. 350 ka; Shackleton, 1987). Marsaglia et al. (1995) note that more than 95% of the interval cored at ODP Site 893 contains less than 5% sand. This is in marked

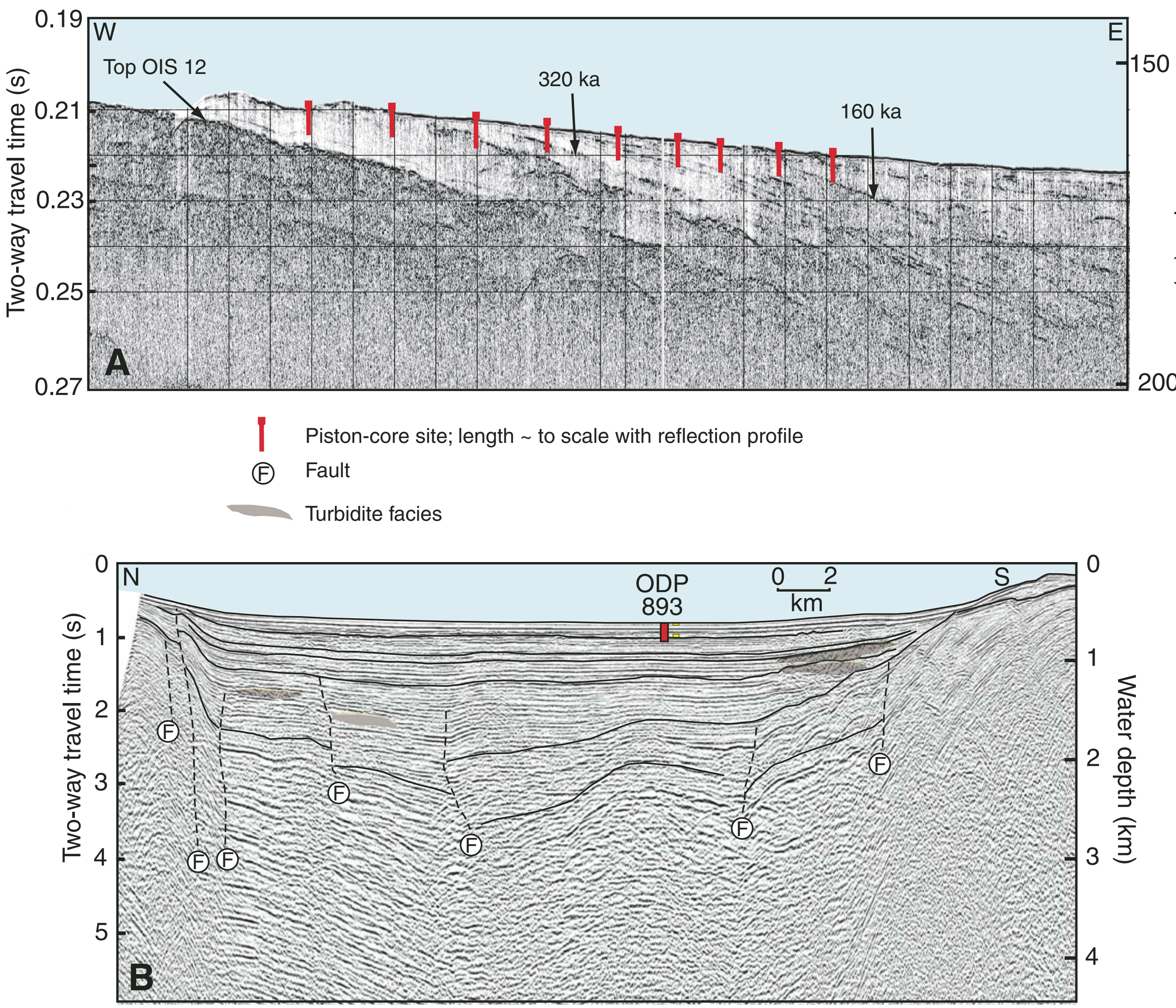


Figure 3. (A) Chirp sonar profile of basin-floor sediments uplifted and exposed on the Mid-Channel Trend. The core schematic representation is drawn to scale, indicating the overlap between adjacent core sites (reconstructed using the format of Nicholson et al., 2006). Profile locations given in Figure 2. (B) Multichannel reflection profile showing paucity of channelized or mounded turbidite facies characteristic of sandy submarine fan bodies in the younger basin fill, except for intervals of more mounded deposition deeper than 0.5 s travel time on the basin margins (gray overlay); modified from Normark et al. (2006a). Ocean Drilling Program (ODP) Site 893 is shown. OIS 12—Oxygen isotope stage 12.

contrast to Santa Monica Basin, where the sediment recovered at Site 1015 is more than 85% sand (Shipboard Scientific Party, 1997). Thus, the lack of mounded, sandy turbidite facies in Santa Barbara Basin is not surprising.

The multibeam shaded-relief image shows that submarine landslides along the northeastern slope of the basin provide the most striking sedimentological relief (Fig. 2). ODP Site 893 was drilled just south of the toe of one of the major submarine slides in the deeper part of the basin. The bulk of the sediment cored at this site is a muddy, mostly hemipelagic sequence with few interbedded turbidites either at highstands or lowstands. Periodic anoxic conditions preserve laminated silty mud intervals as well as distinct uniformly gray muds resulting from floods of the Santa Clara River at the eastern end of the basin. Drilling at Site 893 bottomed in OIS 6 (ca. 160 ka) at 200 mbsf (Shorebased Scientific Party, 1994; Kennett, 1995).

Recent sampling across the Mid-Channel Trend, which is an actively growing, breached, fault-bounded anticline (seen in Fig. 2), confirmed that late Quaternary strata deposited in the deep paleobasin have been uplifted and folded (Nicholson et al., 2006; Fig. 3A). A suite of stratigraphically overlapping piston cores obtained a nearly continuous section with alternating laminated (interglacial) and massive (glacial) silty mud, much like the dominant material cored at Site 893. The section recovered extends the stratigraphic record back to ca. 500 ka based on seismic-reflection correlation with Site 893 (Nicholson et al., 2006).

Santa Monica Basin

The Santa Monica Basin is also a closed basin but in contrast to the adjacent Santa Barbara Basin contains a rich history of coarse-grained sedimentation throughout the late Quaternary. The Hueneme, Mugu, Dume, and Santa Monica Canyons contribute varying amounts of terrigenous sediment to the Santa Monica Basin, constructing fans with the same names (Fig. 4). The Hueneme Canyon, which crosses the Santa Clara delta from nearshore to basin floor, is the major conduit for sediment moving into the Santa Monica Basin, an observation that is not surprising given that nearly 75% of the clastic sediment input to the basin is from the Santa Clara and Ventura Rivers at the western end of the basin (Warrick and Farnsworth, this volume, Chapter 2.2). Nardin et al. (1981) and Nardin (1983) integrate seismic-reflection profiles and piston cores to map the distribution of coarse sediment in the Santa Monica Basin. Conventional bathymetric charts and GLORIA side-scan sonar surveys (Edwards et al., 1996) provide a view of the basin-scale morphology and sediment distribution. Normark et al. (1998), using sleeve-gun seismic-reflection data (~20 m vertical resolution to a depth of 0.4 s below seafloor), provide a chronology of sedimentation patterns for Hueneme Fan and the adjacent, smaller Dume Fan for the past ca. 150 ka. Piper et al. (1999) describe the sedimentary features of the upper 20–80 ms with very high vertical resolution (<1 m) using a deep-tow boomer reflection profiling system and provide the high-resolution, seismic-stratigraphic framework utilized for this study. Normark et al. (2006b) offer a comprehensive view of sedimentation among the separate canyon and fan systems of the Santa Monica Basin since the late Pleistocene. They demonstrate that the Hueneme Canyon–fan system dominates the basin fill, having contributed ~70% of the turbidite accumulation in the past 35 ka.

The depositional architecture and stratigraphic relationships are used to determine basin evolution at two end-member scales (Fig. 5). The southern margin of the basin (Fig. 5A) is defined by submarine topographic highs that are progressively onlapped by distal elements (basin-plain sediment) of the fan complexes. In contrast, the northern margin, which is defined by the continental shelf and across which there is active sediment supply, shows interfingering of sediment from different canyon-fan systems (Fig. 5B).

At much higher spatial and temporal resolutions, recent deposition (6.8 ka–present) on the Hueneme Fan is characterized by laterally shifting depocenters at the mouth of the Hueneme submarine channel (Romans et al., 2009). Figure 6 shows the outlines of depocenters for lobe complexes mapped in the uppermost 30 m of the Hueneme Fan with the distribution of depositional elements on the modern seafloor from Piper et al. (1999). Overall the depocenters shift from east to west, laterally across the middle fan. The youngest intervals (1.7 ka–present) are thickest at the intersection of the prominent right-hand levee and channel-mouth lobe deposits. These high-resolution sedimentation patterns record the incremental construction of the middle-fan area and demonstrate continued activity of Hueneme Canyon as a conduit for sediment to the Santa Monica Basin through the Holocene.

The contribution of sediment to the basin from different feeder systems is a function of the geographic position of the canyon heads with respect to river and/or littoral drift sources as well as the relative position of sea level. Canyons seaward of the mouth of the Santa Clara River can receive hyperpycnal flows during flood stage, and those canyons immediately to the south (down-drift) receive the most sediment from littoral cell sediment transport to the southeast. The Hueneme Canyon, the westernmost of the Santa Monica Basin canyons, is the first feeder to intersect the littoral supply of sediment coming from the Transverse Ranges and the Santa Barbara Basin and lies seaward of the most easterly distributary of the Santa Clara delta. As a result, Hueneme Fan is two orders of magnitude larger than other fans in the Santa Monica Basin.

Normark et al. (2006a) provide a detailed seismic-stratigraphic framework and depositional history for the multiple canyons and fans of the Santa Monica Basin. Sea level has risen nearly 130 m since the LGM lowstand (ca. 20 ka, e.g., Lambeck and Chappell, 2001) to its current position by 6 ka (Fig. 7). During the lowstand, when the shoreline was at or near the modern shelf edge, several feeder canyons delivered coarse-grained sediment from the Santa Clara River delta directly to the Hueneme and Mugu fans (Dahlen et al., 1990; Normark et al., 1998). Littoral drift-supplied sediment was connected to the heads of

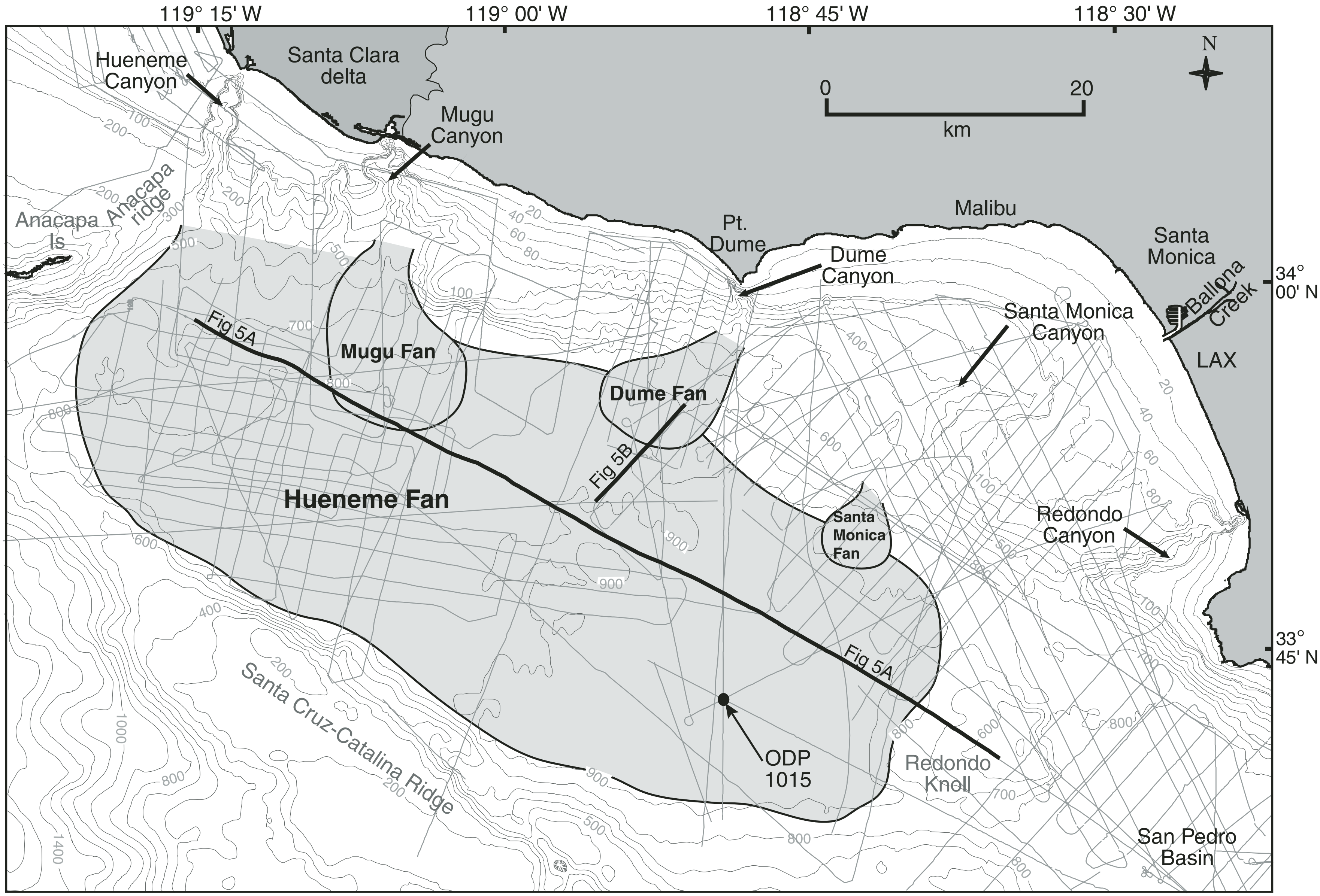


Figure 4. Map of Santa Monica Basin (SMB) showing bathymetry (in meters), major submarine canyon and associated fan systems (Hueneme, Mugu, Dume, and Santa Monica), track-line surveys for all available U.S. Geological Survey (USGS) seismic-reflection data, location of Ocean Drilling Program (ODP) Site 1015, and location of seismic-reflection profiles (Figs. 5A, 5B, and 6B) and detailed map of middle Hueneme Fan (Fig. 6A). LAX—Los Angeles International Airport.

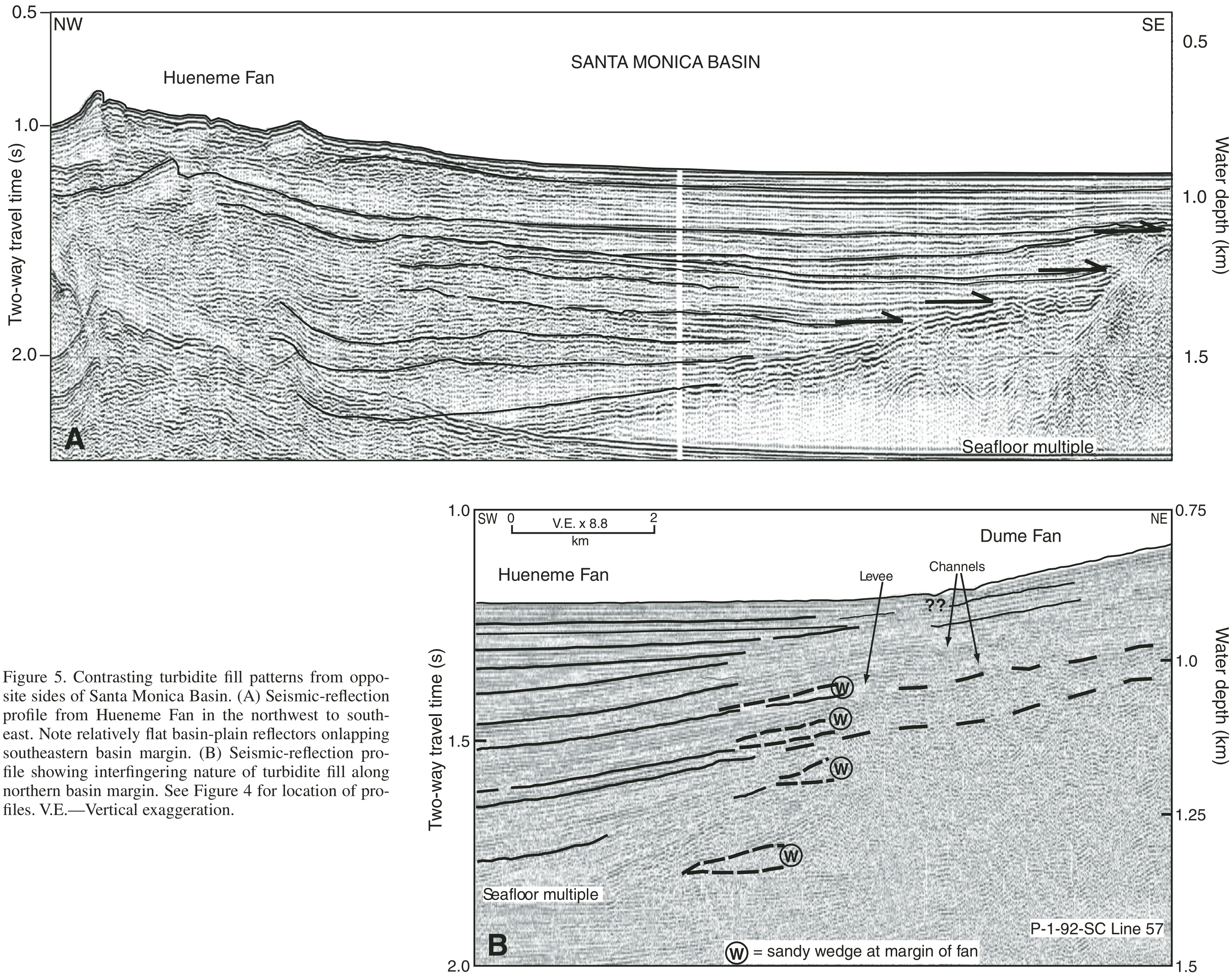


Figure 5. Contrasting turbidite fill patterns from opposite sides of Santa Monica Basin. (A) Seismic-reflection profile from Hueneme Fan in the northwest to southeast. Note relatively flat basin-plain reflectors onlapping southeastern basin margin. (B) Seismic-reflection profile showing interfingering nature of turbidite fill along northern basin margin. See Figure 4 for location of profiles. V.E.—Vertical exaggeration.

Dume, Santa Monica, and Redondo Canyons during this low sea-level period. During post-glacial transgression, the Hueneme and Mugu Canyons maintained a connection with the shoreline as they eroded headward, while secondary canyons in between were abandoned (Piper et al., 1999). Because the shelf is so narrow at Dume Point (<3 km), Dume Canyon also continued to transfer sediment to the basin although at lower rates and volumes relative to Hueneme and Mugu Canyons. Santa Monica Canyon was overrun by rapid transgression, cut off from coarse erosive sediment supply, and abandoned following lowstand and is currently positioned at the modern shelf edge 8 km offshore.

San Pedro Basin

San Pedro Basin, which lies between the Palos Verdes Peninsula and Santa Catalina Island, is separated from the Santa Monica Basin by the Redondo Knoll and from the western Gulf of Santa Catalina to the south by the Avalon Knoll (Fig. 8). The deepest part of the basin is slightly shallower than the deepest part of Santa Monica Basin. The basin receives much of its sediment through the Redondo Canyon at its northern end; the channel leading from the mouth of the canyon takes an abrupt southward turn at the base of the slope (Fig. 8). The multibeam image

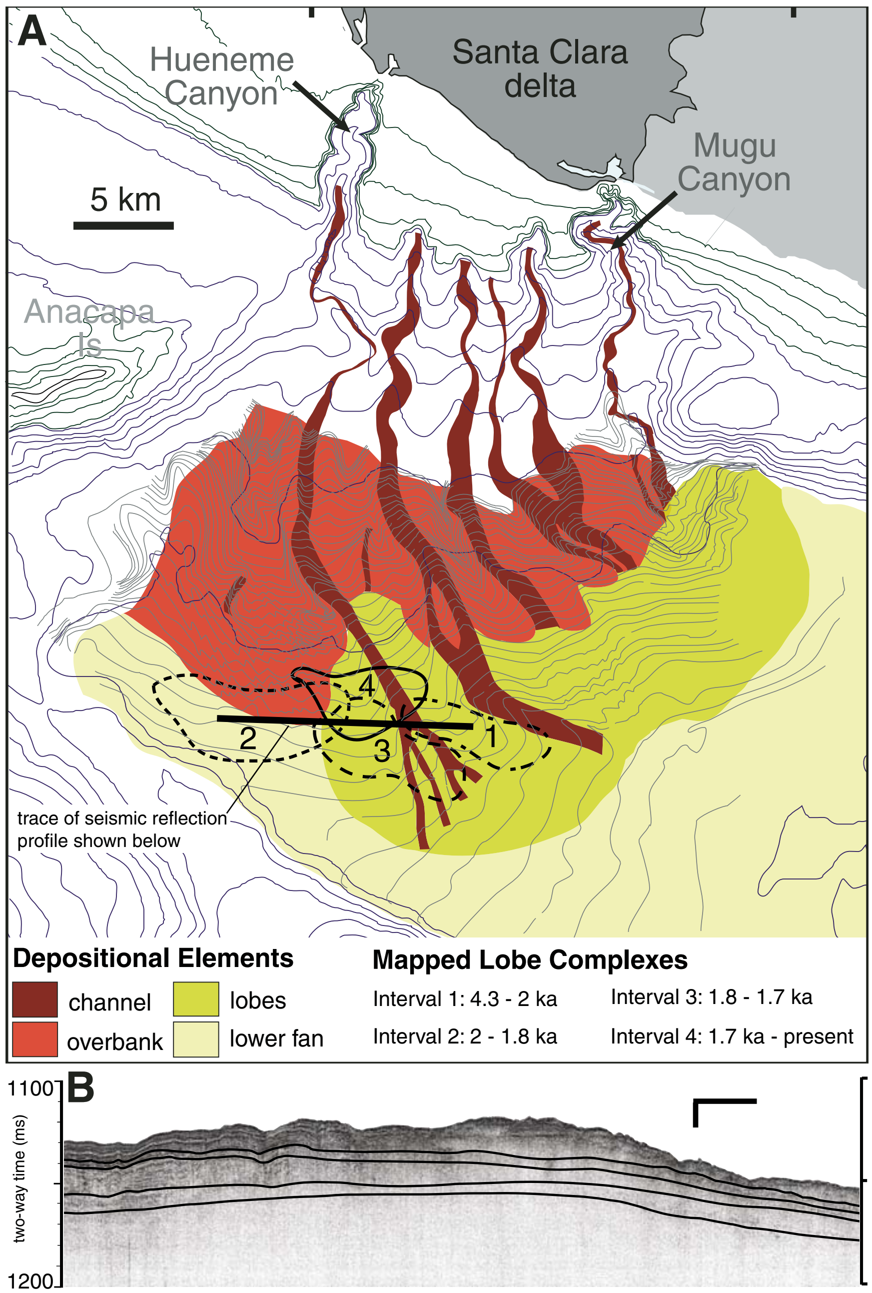


Figure 6. (A) Map of western Santa Monica Basin showing high-resolution bathymetry, distribution of depositional elements on seafloor (from Normark et al., 1998), and location of depocenters for five intervals mapped in the middle Hueneme Fan from 6.8 ka to present. Seismic reflectors were tied to radiocarbon-dated Ocean Drilling Program (ODP) Site 1015 ~25 km downfan in basin plain (Fig. 4) and piston core SMBP2 on the southwest basin margin (see Figs. 2 and 3 in Normark et al., this volume, Chapter 2.6). Depocenter outlines defined as isochron contour representing 80% of maximum thickness. Note lateral shifting of depocenters reflecting construction of lobe complexes near the mouth of Hueneme channel. (B) Huntec deep-tow, seismic-reflection profile (Line 9) across portion of middle fan showing compensation of mapped intervals. See Figure 4 for tracklines of seismic-reflection data used to map lobe complexes.

indicates that flow stripping (sensu Piper and Normark, 1983) of turbidity currents at this sharp bend has probably occurred in the past; the levee crest is breached and an apparent lobe-like deposit extends west toward the northern flank of Redondo Knoll. Thus, Redondo Canyon appears to have provided a minor amount of sediment to Santa Monica Basin.

Redondo Fan is a sand-rich turbidite system and was previously interpreted to have a braided channel pattern (Haner, 1971). The multibeam image of Figure 8 shows the upper fan, seaward of Redondo Canyon, crossed by several channels, two of which appear to connect with the canyon. The thalweg of the eastern channel is continuous with the canyon thalweg, whereas the western channel, which is wider and more prominent in this image, might have been recently cut off from the canyon axis. Several depressions on the upper fan have been cut off near the eastern channel and probably represent older, abandoned channel segments. Only a few nonoverlapping swaths of soundings are available on the west side of the basin. The area south of the upper fan has small-scale hummocky relief common to sandy lobe deposits passing into high-amplitude, diffuse reflection character

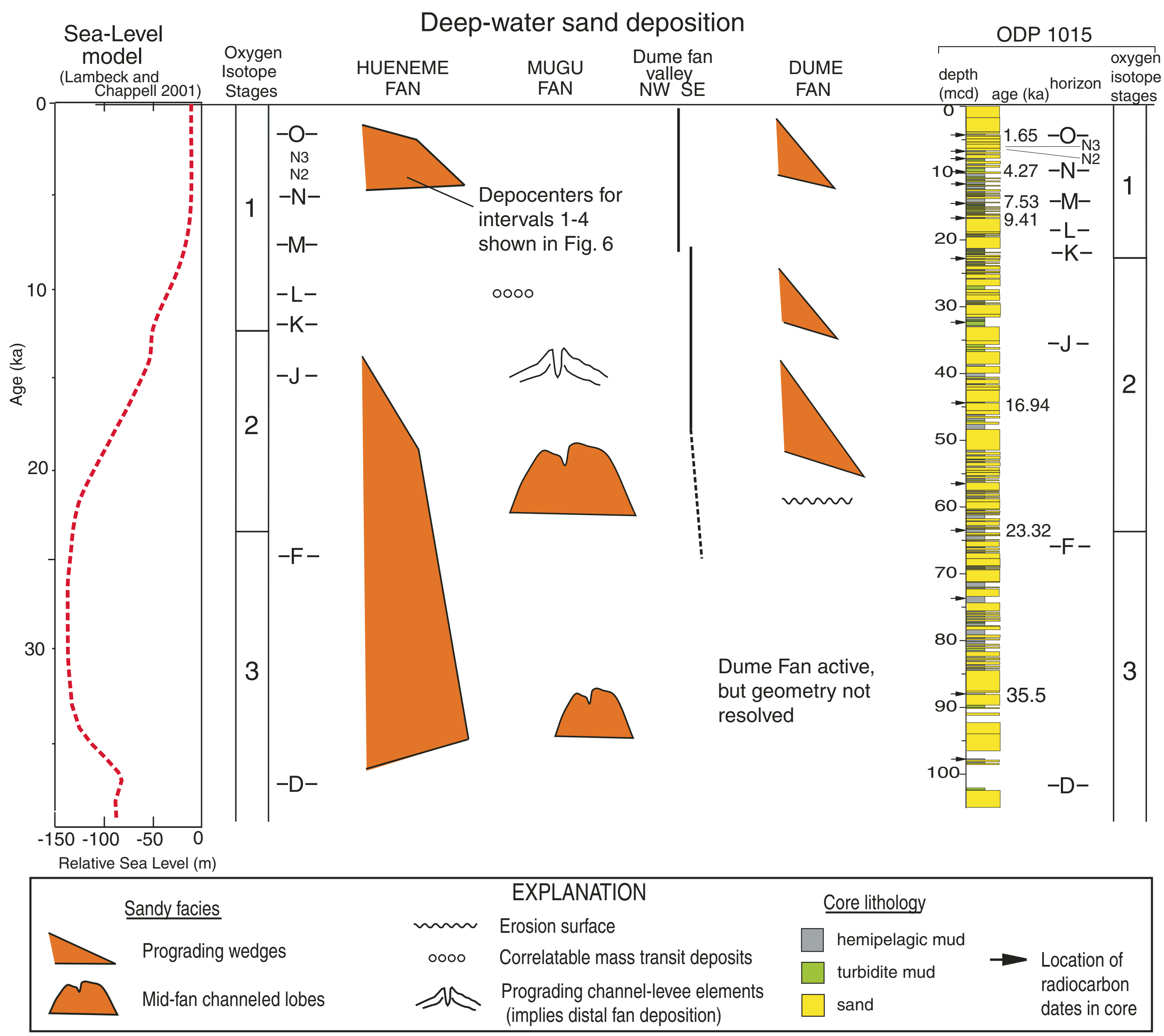


Figure 7. Core data from Ocean Drilling Program (ODP) Site 1015 showing lithology, radiocarbon ages, and key seismic-reflection horizons is compared with sea-level curve (from Lambeck and Chappell, 2001), oxygen isotope stages, and growth stages of Hueneme, Mugu, and Dume submarine fans. Note renewed activity of Hueneme Fan in past 4 ka. See Figure 6 for map of Hueneme Fan depositional elements and seismic-reflection profile of middle fan. Modified from Normark et al. (2006a).

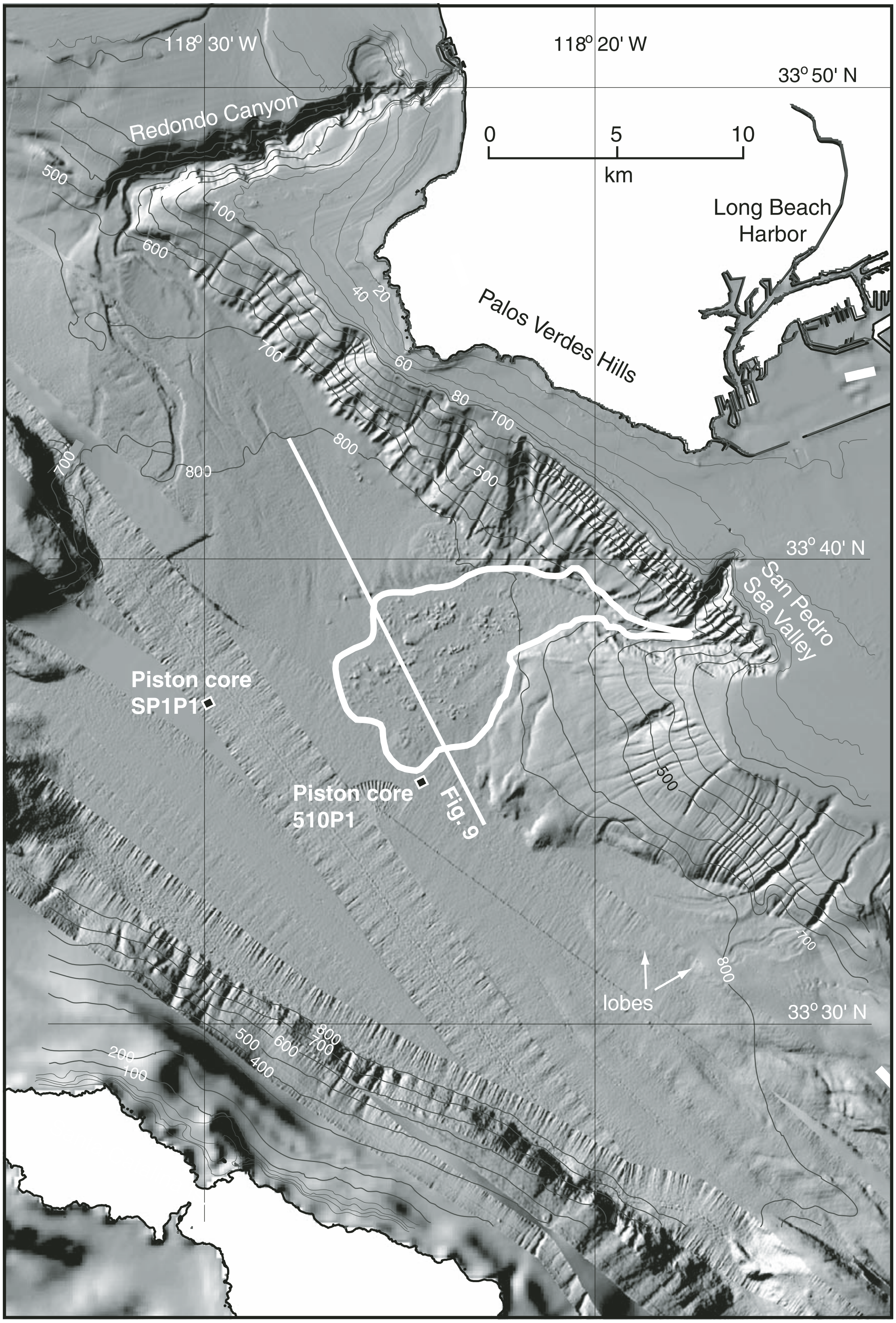


Figure 8. Shaded relief image showing Redondo fan valley and Palos Verdes debris avalanche; the shaded relief is derived from multibeam data described in Gardner and Dartnell (2002). Core positions for 510P1 and SP1P1 (see text) and location of Figure 9 are shown.

in boomer profiles (Fig. 9) that is indicative of sand deposition (Piper et al., 1999). These sandy deposits from Redondo Fan onlap the right-hand levee of a channel extending from the San Pedro Sea Valley (Fig. 9).

Box cores from the upper Redondo Fan described by Haner (1971) were generally sandy. New piston core SP1P1 on the lobe element basinward of the western channel was unable to penetrate more than 32 cm because of the sandy nature of the sediment. A mud unit at 27 cm in this core is radiocarbon dated at 590 yr (calibrated), suggestive of very recent turbidity-current activity on the lobe area of the fan. Recent sampling with a remotely operated vehicle (ROV) along the axis of Redondo Canyon confirms the predominantly sandy input from Redondo Canyon (Normark et al., 2006b). Cores from the axis of the canyon between 500 m and 650 m water depth and from a mud-draped scour in the upper fan valley recovered thin- to medium-bedded sand. In several cores, the uppermost sand bed was within 30 cm or less of the seafloor consistent with deposition during the past 1 ka using adjacent slope rate data (see Normark et al., this volume, Chapter 2.6).

The main part of the San Pedro Sea Valley is plugged by the Palos Verdes debris avalanche. The distal part of the valley has a well-developed levee, where medium amplitude, continuous, slightly wedging internal reflections of the levee sequence indicate deposition of muddier sediment than on Redondo Fan. The base of the relief of the levee of San Pedro Sea Valley at ~25 mbsf laps onto older sediment of the Redondo Fan to the north (Fig. 9).

The Palos Verdes debris avalanche is one of the largest (by volume) late Quaternary, mass-wasted deposits recognized from the inner California Borderland basins during the course of our study (Normark et al., 2004b; Lee et al., this volume, Chapter 4.3). The debris avalanche carried blocks as large as 30 m in height (Fig. 9). Two piston cores taken near the southern margin of the deposit penetrated a muddy flow unit with disrupted silt beds and mud clasts that is correlated with the debris avalanche and has been shown to be ca. 7.5 ka old through radiocarbon dating of overlying and underlying sediment. The debris avalanche moved across well-bedded sediment as shown in the deep-tow boomer record (Fig. 9). The piston cores showed the underlying sediment is thin-bedded sand and laminated silty mud beds consistent with the acoustic facies shown in the boomer records. The source of the sediment is most likely from flows through the San Pedro Sea Valley, based on the character of its northern levee deposit (Fig. 9).

Additional sources of sediment for the San Pedro Basin are from prominent gullies that extend from the shelf edge south of Long Beach harbor to the basin floor at 800 m water depth. Several of the gullies extend on to the basin floor and terminate in lobe-shaped deposits (Fig. 8). No cores are available from these deposits, but they are presumed to be from the LGM because the heads of the gullies are stranded on the outer shelf. Whether these lobes are debris-flow deposits or are of turbidity-current origin is unknown.

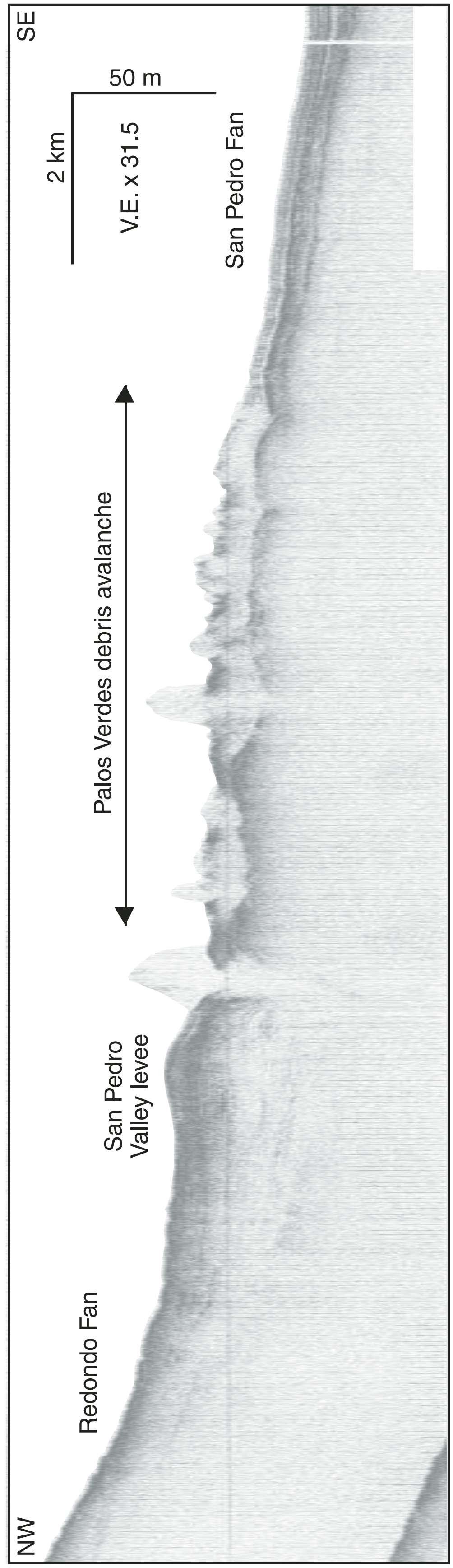


Figure 9. High-resolution, deep-tow boomer profile showing interfingering of deposits from Redondo Fan and San Pedro Sea Valley to the northwest and the large blocks of the Palos Verdes debris avalanche, which fills the San Pedro Valley floor. The irregular surface underlying the debris avalanche suggests it was deposited on earlier mass-wasted material. Profile location given in Figure 8. V.E.—Vertical exaggeration.

Western Gulf of Santa Catalina and Catalina Basin

The area of turbidite sedimentation within what is herein informally called the western Gulf of Santa Catalina is an approximate rectangle demarked by knolls and low ridges (Fig. 10). The basin is separated from San Pedro Basin to the north by the Avalon Knoll and the irregular relief of low, tectonically deforming ridges to the east (see Fig. 12 in Fisher et al., 2004a; Baher et al., 2005). The western boundary is formed by the ridge underlying Santa Catalina Island and by Crespi Knoll. Lasuen Knoll in the east separates the basin from the eastern Gulf of Santa Catalina.

The San Gabriel Canyon heads on the outer San Pedro shelf ~15 km east-southeast of the head of San Pedro Sea Valley. The multiple heads of the canyon coalesce on the mid slope near where the canyon intersects the Palos Verdes fault zone (Fisher et al., 2004a). The San Gabriel canyon-channel system descends the slope to the west flank of Lasuen Knoll, where the channel extending from the San Gabriel Canyon bifurcates. The eastern branch follows the western edge of Lasuen Knoll, marked by the Palos Verdes fault (Fig. 10), where it is at least partially blocked by a mass-wasted deposit, and the channel terminates within the western Gulf of Santa Catalina.

The western branch of the San Gabriel channel system, which has remained active, turns southwest away from Lasuen Knoll, crosses the sill near the south end of the Santa Catalina Ridge, and enters the Catalina Basin to the west. The western branch has been erosionally deepened, leaving broad terraces along its upper reach (Figs. 11A and 11B). The position of the channel locally appears controlled by active faulting (Fig. 11B), and overbank sediment has ponded between the western levee of the channel and the flank of Santa Catalina ridge. South of Avalon Knoll, the western branch of the channel is highly sinuous, but is entrenched until reaching the sill with Catalina Basin (Fig. 10).

The Huntec boomer data from the two branches of the San Gabriel channel shows that before the eastern channel was blocked, its levee prograded over the low-relief levee of the western branch (Fig. 12). The uppermost unit is an acoustically transparent layer that is clearly recognizable except over the floor of the western channel. The transparent layer was cored (red symbol at left side of Fig. 12), and the base of the Holocene is ~1.6 mbsf, which roughly corresponds to the base of the transparent layer (Normark et al., this volume, Chapter 2.6). During the Holocene, above an interval dated at 9.4 ka, the recovered sediment is dominantly mud with only a few silt lenses and was deposited at an accumulation rate of 6.8 cm/ka. In contrast, the accumulation rate during the LGM at this site was 20.8 cm/ka, and the sediment included sand and silty mud units. Thus the San Gabriel Canyon was more active during the LGM, and many flows were able to overtop the 45-m-high levee crest in this eroded part of the western channel.

Seismic-reflection profiles available for Catalina Basin are few in number and are low-frequency multichannel records that do not have the resolution of sedimentary units recorded in the high-resolution multichannel data used for this study. There is no equivalent of boomer data available from the basin, but limited 3.5-kHz profiles generally fail to resolve deeper (i.e., >5 m)

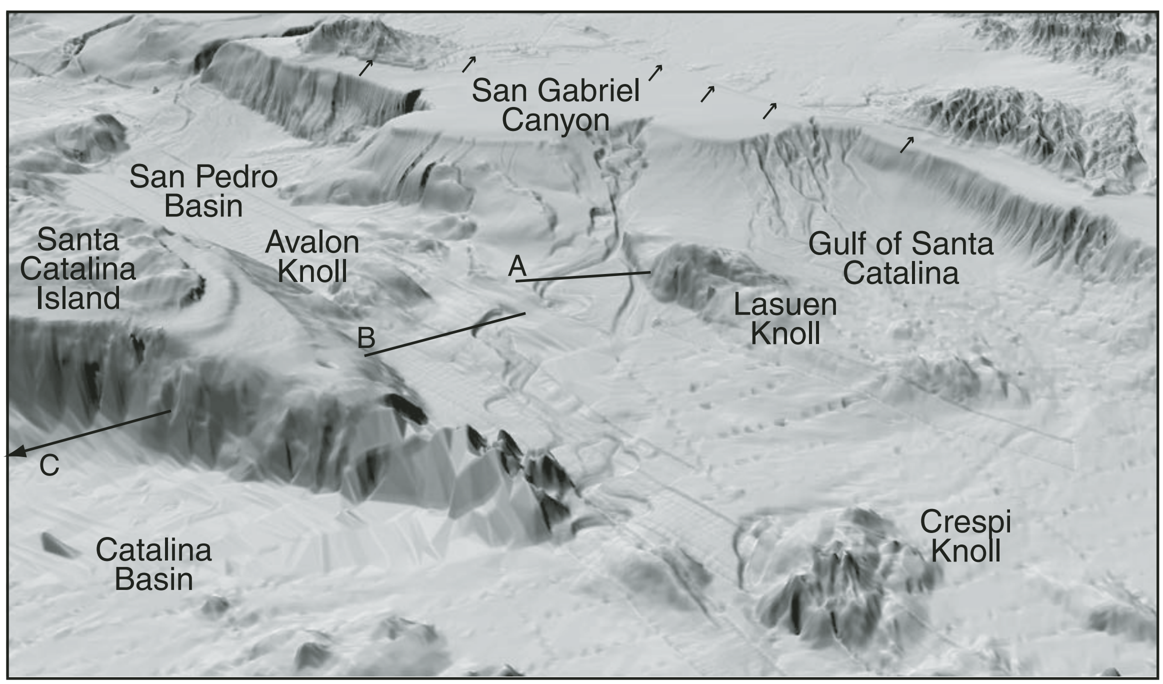


Figure 10. Shaded relief image of area from San Gabriel Canyon on Long Beach shelf and its channel extending through the western Gulf of Santa Catalina to Catalina Basin (modified from Normark et al., 2004a). Small arrows identify modern coastline. Location of profiles in Figures 11 (A, B, C) and 12 (same trackline as A) are shown.

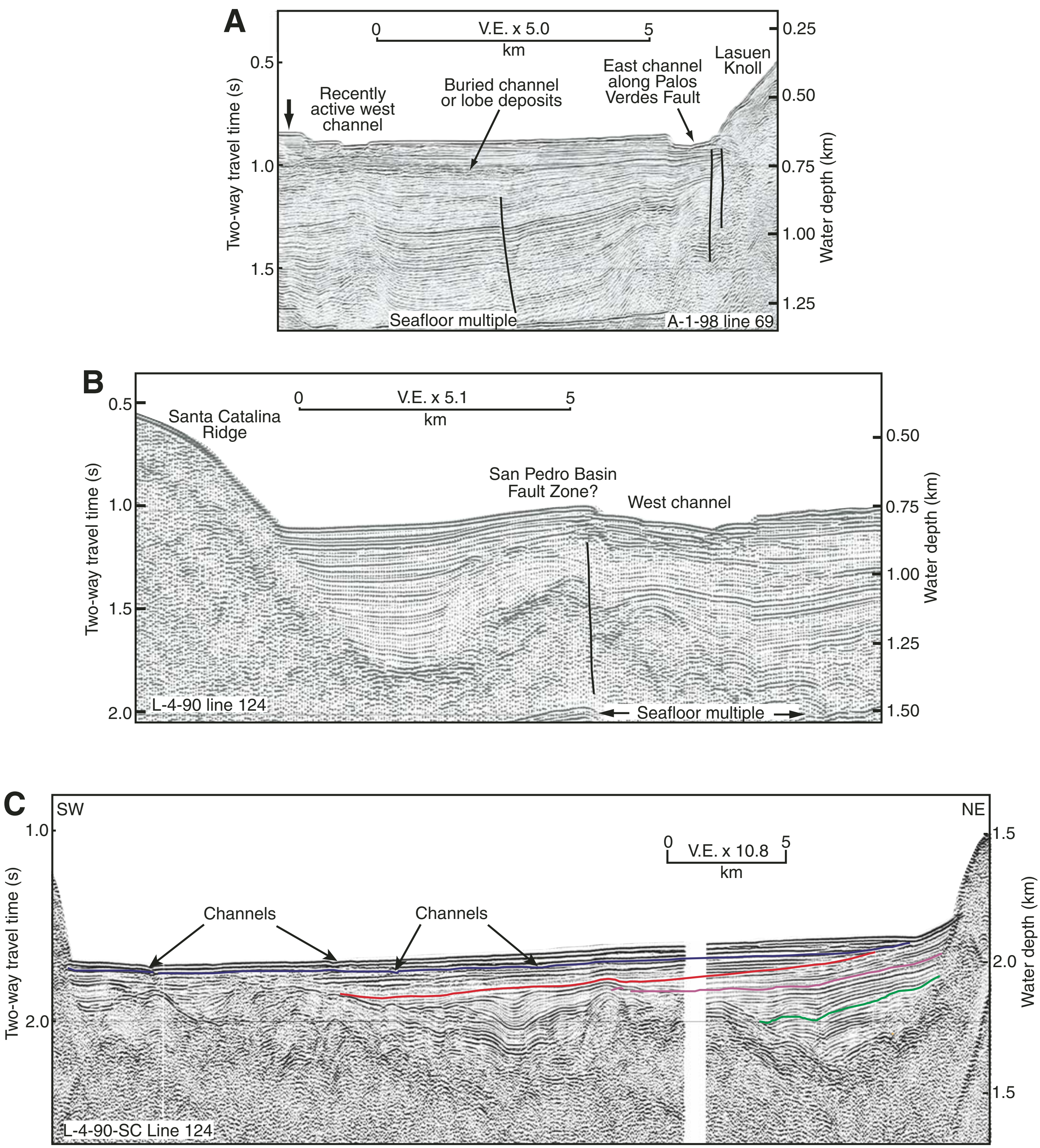


Figure 11. Seismic-reflection profiles from San Gabriel channels in the western Gulf of Santa Catalina and Catalina Basin (adapted from Normark et al., 2004a). Profile locations given in Figure 10. V.E.—Vertical exaggeration.

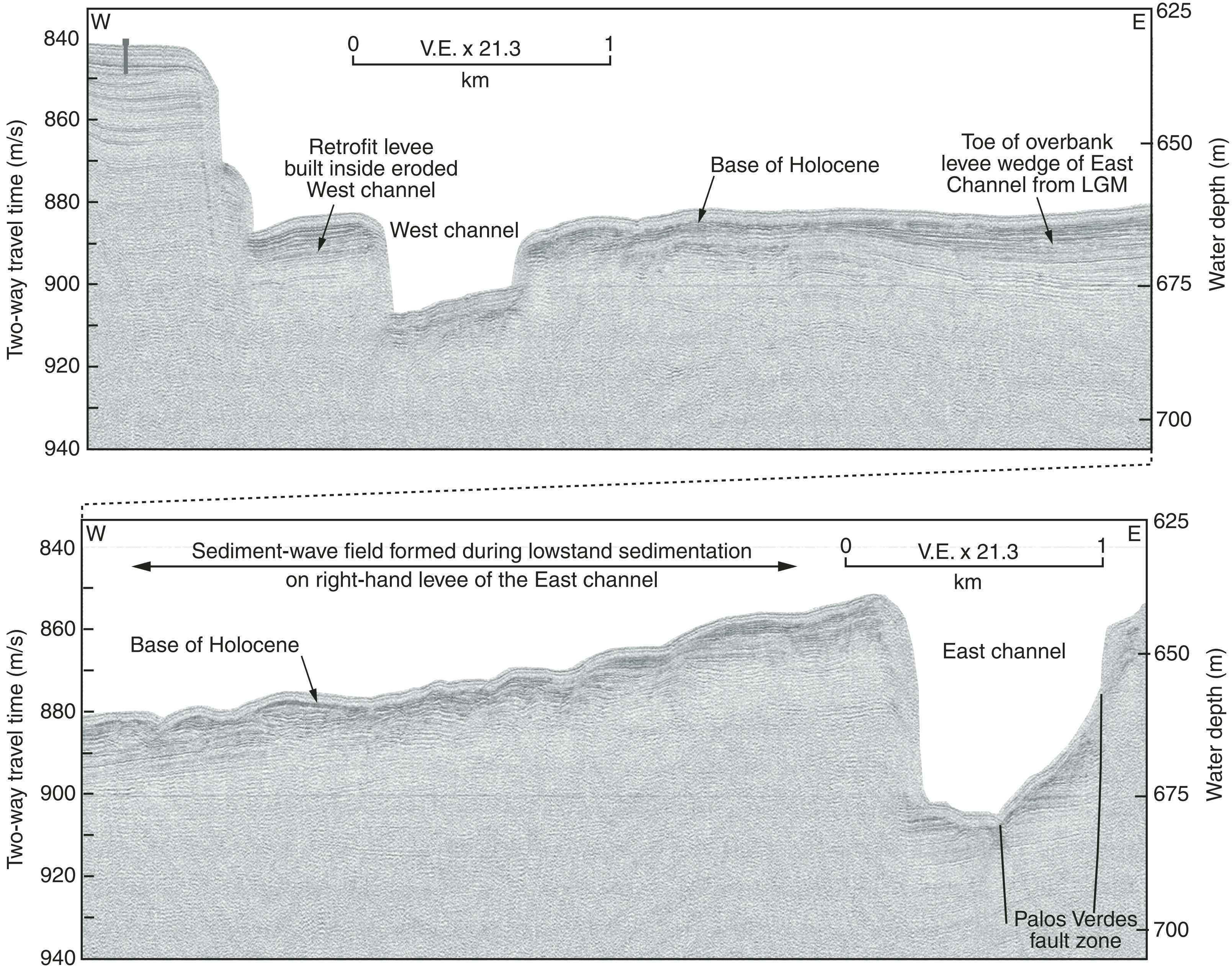


Figure 12. Deep-tow boomer profile line 069-2 showing both branches of the San Gabriel channel in western Gulf of Santa Catalina; this line accompanies the seismic-reflection profile in Figure 11A. Profile location in Figure 10. Abbreviations: LGM—Last Glacial Maximum; V.E.—Vertical exaggeration.

reflectors (Normark et al., 2004a), suggesting that the near-surface sediments are relatively coarse grained.

Available seismic-reflection profiles that cross the middle and southern part of Catalina Basin show a sequence of seismic-stratigraphic units with the acoustic character of turbidite deposits (Normark et al., 2004a). The line-drawing interpretation in Figure 11C delineates sedimentation units that can be roughly correlated among the reflection profiles in Catalina Basin. The reflection character of the upper units down to below the green reflector is typical for turbidite deposits. Low-relief turbidite channels are seen both on the present seafloor and on the blue surface, which is the top of a thicker underlying turbiditic interval (Fig. 11C). Especially at the margins of the basin, the sedimentation units show progressively more tilting with age. Based on comparison with Santa Monica Basin stratigraphy, the sequence in Catalina Basin is interpreted to record episodes of turbidite deposition during sea-level lowstands and little or only hemipelagic sedimentation during highstand conditions (Normark et al., 2004a).

Thus, available data indicate that the uppermost Catalina Basin fill is the result of turbidity currents reaching the basin during the LGM. The thicker turbidite sequence above the red reflector (Fig. 11C) may have been deposited during OIS 6 when sea level was at least as low as during the OIS 2 but for a longer period (Shackleton, 1987). Thus, the San Gabriel Canyon and its predecessors might have been feeding sediment to Catalina Basin for the past 160 ka. Prior to breaching the sill to reach Catalina Basin, the sinuous channel pattern (Fig. 10) might indicate a low-relief, ponded sediment fill in western Gulf of Santa Catalina.

Eastern Gulf of Santa Catalina

The eastern Gulf of Santa Catalina is fed by the Newport Canyon–channel system, which leads from the eastern San Pedro Shelf break, extends southeast for ~40 km, and then turns west-southwest for 25 km to reach the north side of Crespi Knoll (Fig. 13). At this point, the channel turns south along the west side of the knoll, crossing the southeast quadrant of western Gulf of Santa Catalina, and enters San Diego Trough (discussed below). The Newport Canyon–channel system is thus longer (~130 km) than other systems in the Borderland. It remained active throughout the Holocene, with multiple canyon-head point sources of sediment at the edge of a prograding delta and is fed directly by the Santa Ana River and the San Diego Creek (see Warrick and Farnsworth, this volume, Chapter 2.2, for watershed details). Today, one of the canyon heads on the eastern part of the delta is active. This interpretation is based on lack of hemipelagic sediment draping the channel floor and USGS piston cores containing recently deposited turbidites (Normark et al., this volume, Chapter 2.6). Newport Canyon also received littoral drift-fed sediment from other rivers feeding the San Pedro littoral cell, including the Los Angeles and San Gabriel Rivers that drain the Peninsular Range and San Gabriel mountains (Fig. 13; Inman and Brush, 1973; Brownlie and Taylor, 1981; Warrick and Farnsworth, this volume, Chapters 2.2 and 2.3).

Bathymetric relief created by structural deformation, coupled with the seafloor gradient, contributes to the coalescing of the Newport Canyon tributaries near the eastern flank of Lasuen Knoll (Fig. 14). Prominent scours and sediment waves draped by hemipelagic mud indicate erosive canyon-channel system activity during lower sea level (lower part of Fig. 15A and boomer profile of Fig. 15B).

The Newport channel turns west ~35 km seaward of Oceanside (Fig. 13). This abrupt change in direction resulted from the San Mateo thrust to the east blocking southeastward progradation of the Newport system (Graham and Bachman, 1983; Fischer and Mills, 1991; Ryan et al., this volume, Chapter 4.5). The Newport channel wraps around the northwestern flank of Crespi Knoll and enters San Diego Trough from the north. The southeastern extension of Santa Catalina Island inhibits westward progradation of the Newport channel (Fig. 13).

San Diego Trough

The San Diego Trough is an elongate basin fed predominantly by three late Quaternary canyon-channel systems (Fig. 13). It is bounded to the west by Thirty Mile Bank, and to the east by Coronado Bank. Newport channel enters the San Diego Trough from the north and deposits sediment longitudinally along the basin axis. The Oceanside and La Jolla systems contribute sediment orthogonal to the basin axis.

Chronology in San Diego Trough is based on well-constrained estimates of sedimentation rates for the Holocene and late Pleistocene on the western overbank of the La Jolla Canyon–channel system. The Holocene sedimentation rate is ~12 cm/ka and is inferred from relatively shallow (~2–3 m), USGS Coastal and Marine Geology (CMG) piston cores collected on 1999 and 2003 cruises. The late Pleistocene sedimentation rate is ~175 cm/ka and is inferred from deep (70 m) cores collected during experimental drilling into La Jolla Fan for Project Mohole (1958–1966) (Inman and Goldberg, 1963). Age estimates based on sedimentation rates can be refined in the light of results from Santa Monica Basin (Normark et al., 2006a), which showed that major inputs of coarse sediment to the basin floor begin at times of rapid fall in sea level, for example at the OIS 5-4 (75 ka) and OIS 3-2 (25 ka) transitions (Lambeck and Chappell, 2001). Present water depths of the landward lip of submarine canyon heads can be compared with the OIS 2-1 global sea-level curve of Fairbanks (1989) in order to date the times when canyon heads became inactive during the transgression.

Turbidite Systems of the Eastern Gulf of Santa Catalina and San Diego Trough

Four canyon-channel systems contributed sediment that built prominent submarine fans in the eastern Gulf of Santa Catalina and San Diego Trough. Only the La Jolla system has been studied in detail (Shepard and Buffington, 1968; Shepard et al., 1969; Normark, 1970; Piper, 1970; Graham and Bachman, 1983). This

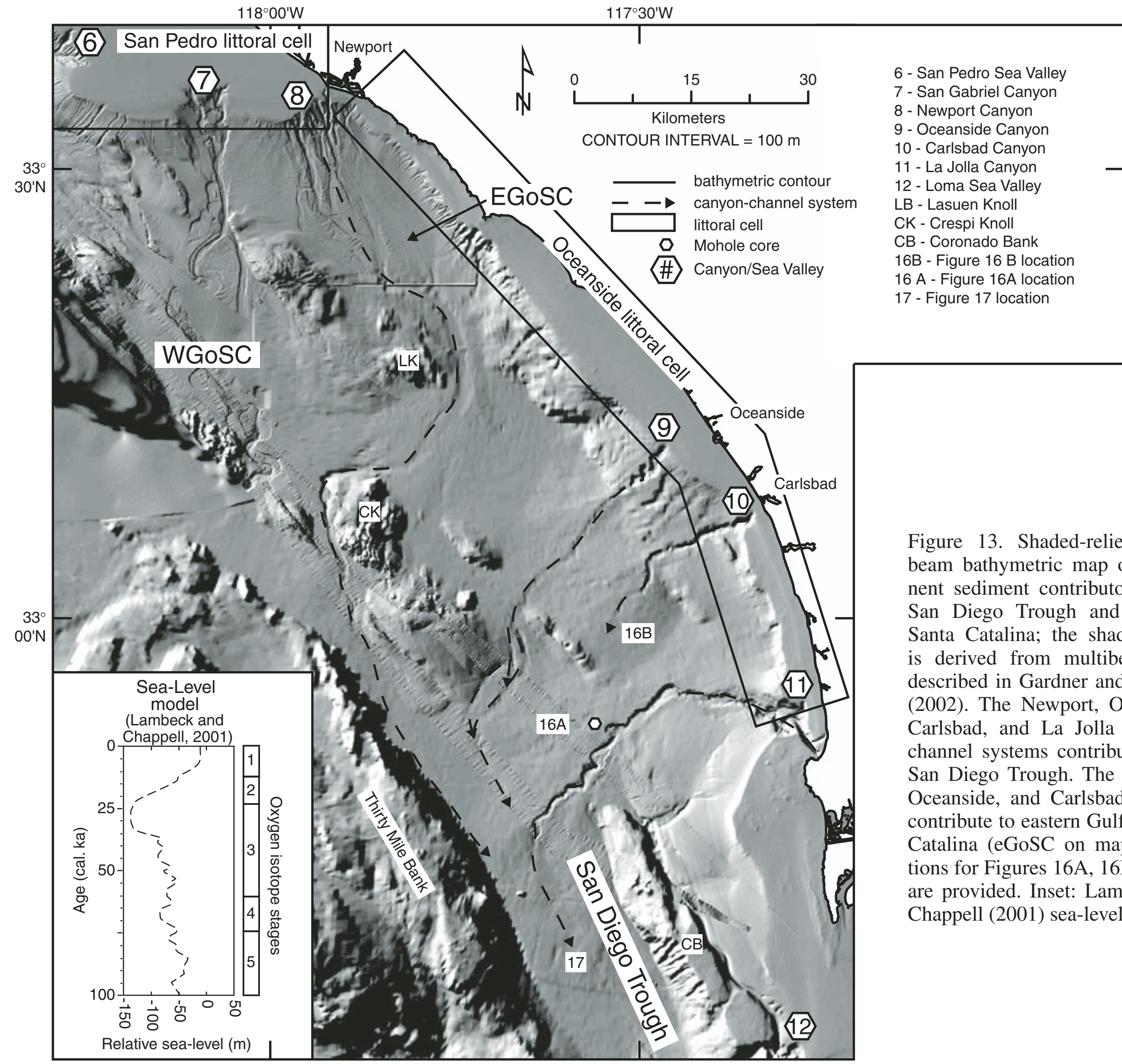


Figure 13. Shaded-relief, multibeam bathymetric map of prominent sediment contributors to the San Diego Trough and Gulf of Santa Catalina; the shaded relief is derived from multibeam data described in Gardner and Dartnell (2002). The Newport, Oceanside, Carlsbad, and La Jolla Canyon–channel systems contribute to the San Diego Trough. The Newport, Oceanside, and Carlsbad systems contribute to eastern Gulf of Santa Catalina (eGoSC on map). Locations for Figures 16A, 16B, and 17 are provided. Inset: Lambeck and Chappell (2001) sea-level curve.

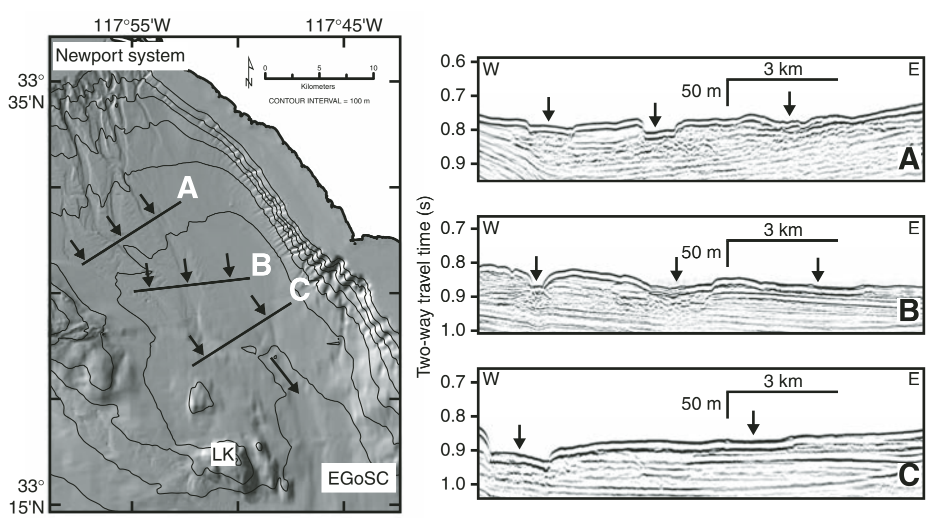


Figure 14. Shaded-relief bathymetric map of the eastern Gulf of Santa Catalina and the Newport Canyon–channel system (left) and multichannel seismic (MCS) profiles (right) showing Newport Canyon tributaries coalescing near the eastern flank of Lasuen Knoll (LK); the shaded relief is derived from multibeam data described in Gardner and Dartnell (2002). Arrows indicate channel locations. Black lines on map indicate MCS profile location.

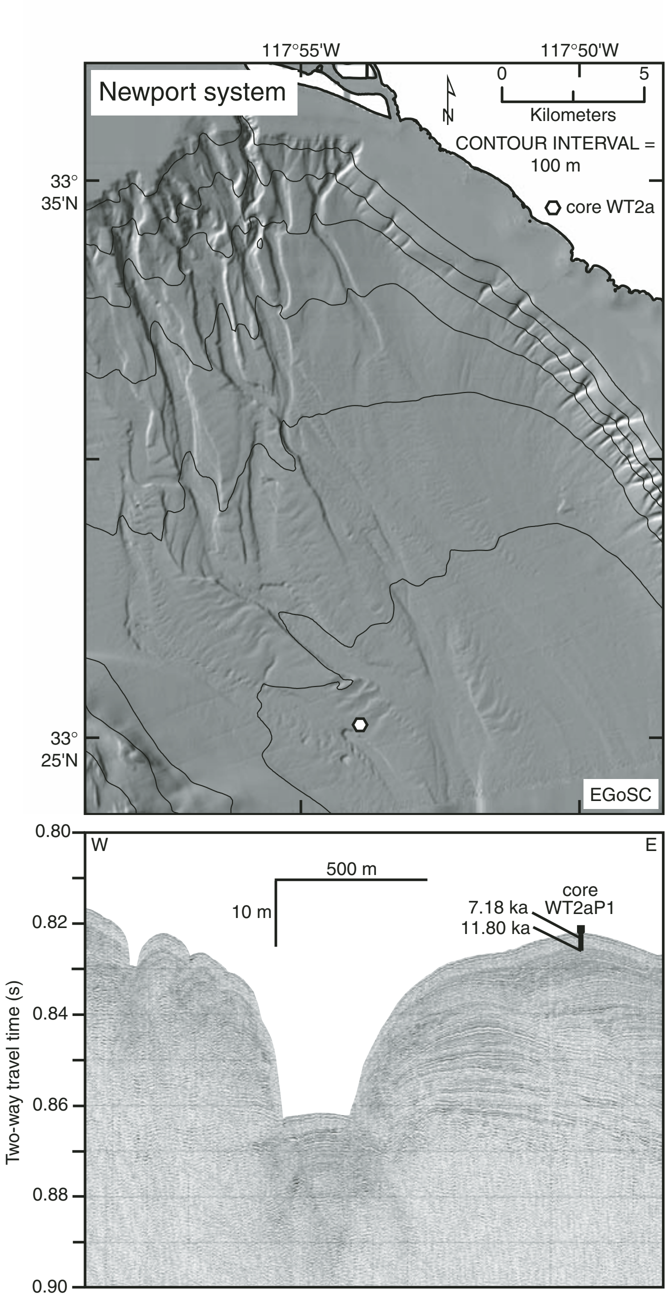


Figure 15. Shaded-relief bathymetric map of the Newport Canyon–channel system showing Newport Canyon tributaries coalescing in the eastern Gulf of Santa Catalina (above) and Huntec seismic-reflection profile showing core location WT2a (below); the shaded relief is derived from multibeam data described in Gardner and Dartnell (2002). Note the prominent scours and sediment waves on the map. A prominent scour depicted on the Huntec profile is draped by hemipelagic mud, suggesting inactive turbidity-current–related sedimentation. Nearby core WT2a provides an age of ca. 12 ka for the base of the hemipelagic mud.

section reviews the unique canyon-channel systems and their complex late Quaternary history in this exceptional region of the inner California Borderland.

Newport Canyon–Channel System

Newport channel is a longitudinal source of sediment to San Diego Trough, and its depositional lobes interfinger with sediment from lateral sediment contributors, namely the Oceanside and La Jolla Canyon–channel systems, which restrict its deposits to the western portion of San Diego Trough. The Newport channel terminates in San Diego Trough as a series of depositional lobes, with the modern system terminating against extensive La Jolla Canyon–channel system depositional lobes. Correlating seismic-reflection horizons from core locations discussed above shows that the Newport Canyon–channel system has been active in the San Diego Trough likely at least since the abrupt fall in sea level at the OIS 3-2 transition.

Oceanside Canyon–Channel System

The presence of hemipelagic mud draping the Oceanside channel floor suggests that the Oceanside Canyon–channel system is currently inactive but was active during the LGM before shoreline transgression stranded its canyon head on the outer shelf (Fig. 13), at the widest portion of continental shelf between Dana Point and La Jolla. The canyon head was supplied by littoral drift from sediment from the Santa Margarita River to the north and directly by the San Luis Rey River (Fig. 13; Inman and Brush, 1973; Brownlie and Taylor, 1981; Warrick and Farnsworth, this volume, Chapters 2.2 and 2.3). Both rivers have their headwaters in the Peninsular Ranges. Since the Oceanside Canyon head was drowned, sediment from both rivers has been feeding the Carlsbad and La Jolla Canyon–channel systems via littoral drift.

The Oceanside Canyon–channel system might have received different amounts of littoral drift-fed sediment depending on the location of the shoreline (Fig. 13). For example, at the LGM, Oceanside Canyon head was at the paleoshoreline (following the sea-level curve of Lambeck and Chappell, 2001). This might have allowed it to intercept littoral sediment before it could reach the La Jolla Canyon head. During shoreline transgression (OIS 1-2 transition; Lambeck and Chappell, 2001), the Oceanside Canyon head was gradually drowned, and the La Jolla Canyon head received a majority of the sediment from the Oceanside littoral cell.

In the San Diego Trough, MCS reflection profiles show that the Oceanside channel was oriented southeast and terminated as a series of depositional lobes oriented subparallel to the basin axis. A number of these lobes were deposited over an abandoned La Jolla channel, and provided bathymetric relief for the modern La Jolla Submarine Fan (Fig. 16A; see also Graham and Bachman, 1983).

Multichannel seismic-reflection profiles show that the Oceanside system changed its trend after the OIS 3-2 (25 ka) transition (Fig. 16A). The channel circumvented the previously deposited depositional lobes in order to enter the San Diego Trough. The channel terminated as two depositional lobes oriented subparallel to the basin axis against prominent, laterally prograded, La Jolla Canyon–channel system depositional lobes (Fig. 16A). A relatively thin (~1.5 m thick) wedge of La Jolla overbank sediment separates the two depositional lobes (Fig. 16A).

Carlsbad Canyon–Channel System

Multichannel seismic profiles show that the Carlsbad Canyon–channel system is a less extensive sediment contributor to the San Diego Trough than either the Newport or Oceanside Canyon–channel system (Fig. 13). The radiocarbon age from the Mohole core on the adjacent La Jolla Submarine Fan suggests that the Carlsbad Canyon–channel system initiated >40 ka. At present, this canyon-channel system is inactive with the canyon head in ~50 m water depth. Carlsbad Canyon head is located at a relatively narrow portion of the continental shelf, which allowed it to keep pace with shoreline transgression during the earlier parts of the OIS 2-1 transgression (Fig. 13). Ogawa (1989) suggest that a pressure ridge at the shelf edge along a left step of the dextral Newport-Inglewood–Rose Canyon fault zone may have diverted the drainages of ephemeral creeks. During sea-level lowstand, these creeks may have coalesced against the pressure ridge and their effluents incised the Carlsbad Canyon head. The Carlsbad channel may receive additional sediment from proximal erosional slope-gully systems to the north (Fig. 13).

The Carlsbad system terminated following the OIS 2-1 transition after depositing numerous stacked depositional lobes between the unnamed ridge and the steep shelf break (Fig. 16B).

La Jolla Canyon–Channel System

Deep-penetrating MCS profiles show that the La Jolla Canyon–channel system has existed since OIS 4 or 3; however, a more modern system has remained active for the past 16 ka and was probably initiated coincident with OIS 2 transgression of sea level (Fig. 16A). The age assignment is extrapolated from the nearby Mohole core site using available seismic-reflection data. The La Jolla system remained active through the Holocene, as La Jolla Canyon head erosion kept pace with shoreline transgression (Fig. 13). To the south of the La Jolla Canyon, resistant Cretaceous rocks that form the La Jolla peninsula block southerly transport of littoral drift-fed sediment from the Oceanside littoral cell, and the beneficiary is the La Jolla system (Inman and Brush, 1973; Strand, 1962). The La Jolla Canyon head is a point source of sediment. It lacks a fluvial sediment source, and presently receives littoral drift-fed sediment from the Oceanside littoral cell (including the Santa Margarita, San Luis Rey, and San Dieguito Rivers, and the San Juan Creek) (Fig. 13).

The evolution of the La Jolla system is tied to that of the Oceanside system. Multichannel seismic profiles indicate a present predominant erosional character as La Jolla channel incises through broad Oceanside depositional lobes underlying the upper La Jolla Fan (Fig. 16A). The system is slightly depositional on the upper fan, where levee heights are shallow enough for turbidity-current flows to spill over and contribute sediment to overbank regions. The system terminates at the southern end of the San Diego Trough as a series of prominent depositional lobes that have blocked progradation of the Newport and Oceanside Canyon–channel systems (Figs. 13 and 17). La Jolla depositional lobes appear to compensationally stack over one another, with the most recent lobe restricted to the western portion of the San Diego Trough by previously deposited lobes. La Jolla fan sediment might extend to the leveed flanks of the channel extending from Coronado Canyon, which then leads to Navy Fan in the San Clemente Basin farther west (Normark and Piper, 1972).

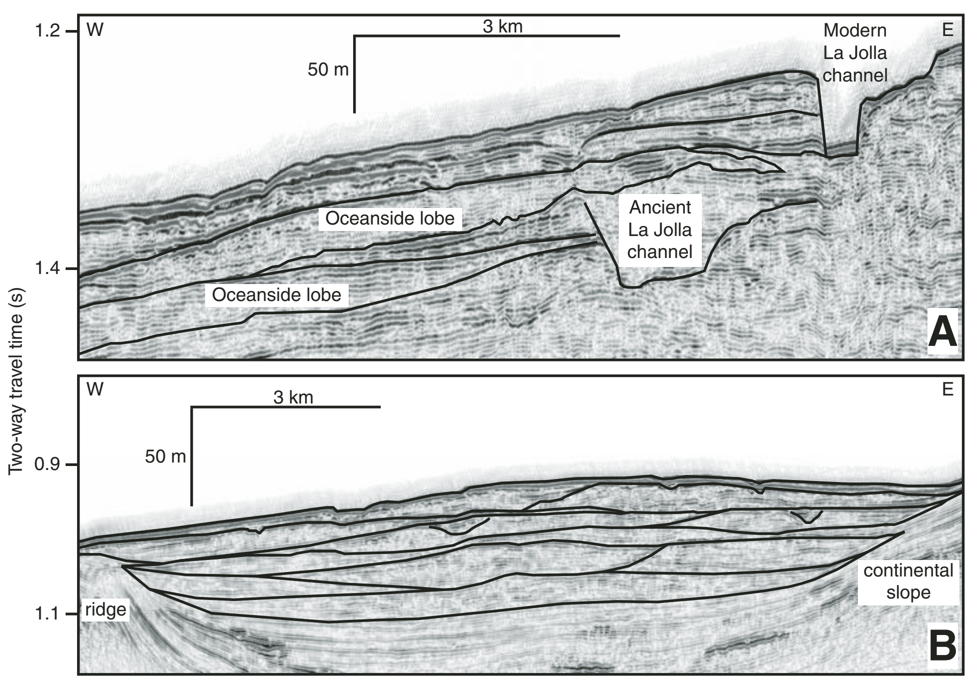


Figure 16. (A) Multichannel seismic (MCS) profile showing the western levee of La Jolla channel. Oceanside depositional lobe (4) was deposited over an abandoned La Jolla channel (1), and provides bathymetric relief for the modern La Jolla Submarine Fan. The modern La Jolla channel is identified by the number “2.” (A) La Jolla depositional lobe is identified by the number “3.” (B) MCS profile showing Carlsbad system depositional lobe development. The Carlsbad system exhibits a marked depositional character relative to the other turbidite systems contributing to the San Diego Trough. It fills a mini-basin bounded by an unnamed ridge to the west and the continental slope to the east (Graham and Bachman, 1983).

San Clemente Basin and Navy Fan

A complex horst, decreasing in width and elevation southward, separates San Diego Trough from the next outboard basin, San Clemente Basin, which is itself divided by horsts into a northern and a southern basin (Fig. 18). In southern San Diego Trough, Coronado Canyon lies 15 km offshore from the mouth of the Tijuana River, just north of the Coronado Islands. With this wide shelf, it seems likely that the canyon was active only at marine lowstands. Coronado Canyon leads to Coronado fan valley, which has built a constructional feature in southern San Diego Trough and then crosses the horst south of Navy Bank and leads to Navy Fan in the eastern part of south San Clemente Basin.

In seismic-reflection profiles, a regional subbottom reflection (shown in red in Figs. 19–21) can be traced over all of southern San Diego Trough and is tentatively correlated on reflection character and thickness into San Clemente Basin (Fig. 19). On the basin floor, beneath this reflection is a somewhat draping package of lower amplitude reflections. Above this regional reflection are higher amplitude reflections that in places onlap the reflection. The regional reflection corresponds to an unconformity over shallow anticlines (Fig. 20A). This regional reflection can be traced to the Mohole site, where it is ~100 ms subbottom. In the Mohole test boring, an age of 40 ka (calibrated years) was obtained at a subbottom depth of 80 m (Inman and

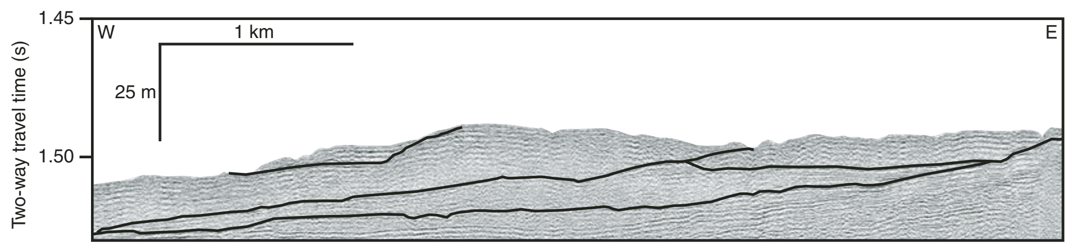


Figure 17. Interpreted Huntec seismic-reflection profiles showing La Jolla system terminating as compensationally stacked depositional lobes. The lobes block progradation of the Newport and Oceanside Canyon–channel systems.

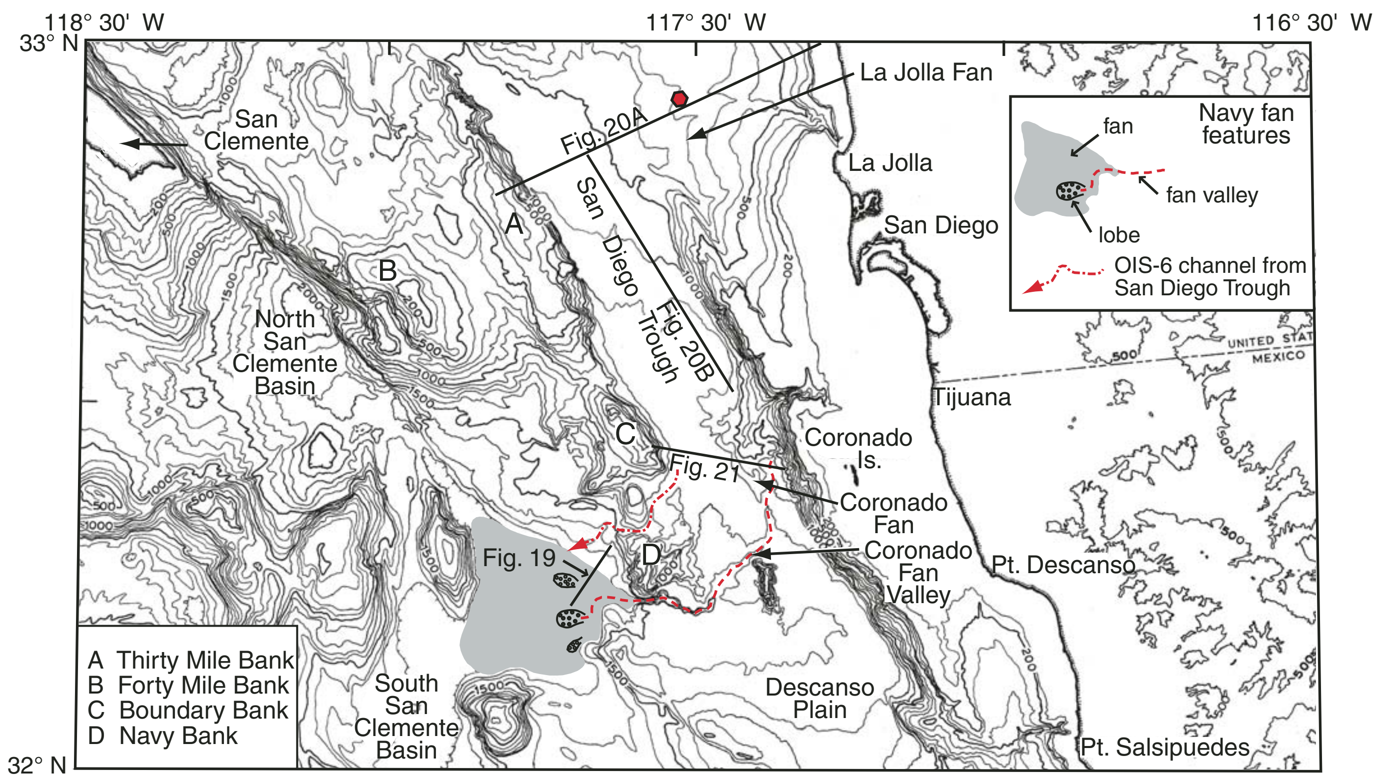


Figure 18. Map of San Clemente Basin and southern San Diego Trough (based on Legg, 1991, and Legg, 2006, written commun.); contour interval is 100 m. Location of seismic-reflection profiles in Figures 19–21 are shown along with general area of Navy Fan. OIS 6—oxygen isotope stage 6.

Goldberg, 1963). The regional reflection is therefore interpreted to represent the transition from onlapping lowstand turbidites of OIS 4 to underlying, predominantly hemipelagic or distal muddy turbidites of the OIS 5 highstand, when the Coronado Canyon would have been disconnected from the Tijuana River mouth and the closest turbidite supply was from La Jolla Fan or the Newport Channel system. This regional reflector thus allows the OIS 4-1 succession to be identified throughout southern San Diego Trough and San Clemente basin. Figure 19 shows a tentative interpretation of the deeper stratigraphy of San Clemente basin, with OIS 7 and 9 highstands recognized as having similar reflection character and geometry to OIS 5 deposits.

In the OIS 4-1 interval, axial seismic-reflection profiles in San Diego Trough (Fig. 20B) pass from a more mounded geometry on distal La Jolla Fan to subparallel basin-floor reflections that onlap deposits of Coronado Fan. These Coronado Fan deposits directly overlie the regional reflection and may thus date from the OIS 4 lowstand. Seismic-reflection profiles across Coronado Fan show a broad channel fill some 200 ms thick that overlies poorly imaged stratified lower amplitude reflections (Fig. 21). This broad channel floor and its corresponding high right-hand levee (3 in Fig. 21) are overlain by successively narrower channels and their corresponding inner levees (2 and 1 in Fig. 21): a very similar pattern is seen in the evolution of Hueneme Fan Valley. The modern levee appears to have started to grow at about the top of the OIS 4 fan lobe deposit (Figs. 20B and 21). This lobe was probably fed by an older fan valley that flowed almost due west from Coronado Canyon.

On the western side of San Diego Trough, there is a prominent irregular erosion surface within the packet of sediment deposited during OIS 6. This erosion surface is illustrated in Figure 21 and is also well imaged in a southwesterly trending, multichannel profile that crosses San Diego Trough just north of the Exclusive Economic Zone (EEZ) boundary (see Fig. 1 and Line W75-441, USGS ID W-3-75SC [WesternGeco, 1975] in the National Archive of Marine Seismic Surveys, http://walrus.wr.usgs.gov/NAMSS). The erosion surface appears to pass eastward into stratified, high-amplitude, basin-floor reflections. This prominent unconformity is interpreted as a paleochannel developed along the western margin of San Diego Trough. The unconformity is not clearly visible on profile Channel 6 Line C of Smith and Normark (1976), which may indicate that the paleochannel crossed the ridge and entered San Clemente Basin north of Navy Bank. The size and northward extent of the erosion surface suggests that the channel was fed not only by Coronado Canyon but also by canyon systems farther north in San Diego Trough.

The Coronado Fan in southern San Diego Trough shows important differences from turbidite systems farther north. In its facies and scale, OIS 3-2 Coronado Fan closely matches Hueneme Fan. Both systems would have been fed by a bedload-rich river entrenched across the shelf as a result of the rapid fall in sea level at 30–25 ka (Normark et al., 2006a), resulting in efficient transport of coarse bedload and growth of a high right-hand levee from hyperpycnal flows. Coronado Canyon was also an active sediment conduit during the OIS 4 lowstand, building a lower fan wedge probably from a fan valley that extended due west of the canyon. At highstands of sea level, in OIS 5 (and presumably in early interglacial highstands of OIS 7 and 9), Coronado Canyon was detached from sediment supplied by the Tijuana River and stranded at the shelf edge. This led to the development of a prominent acoustically transparent unit in southern San Diego Trough (Fig. 21), with an order of magnitude lower sedimentation rate than during OIS 2-4. Northward, this acoustically transparent unit becomes less prominent (Fig. 20B) with the deposition of distal turbidites during highstands from La Jolla and Newport Canyons. The low sedimentation rates at highstands

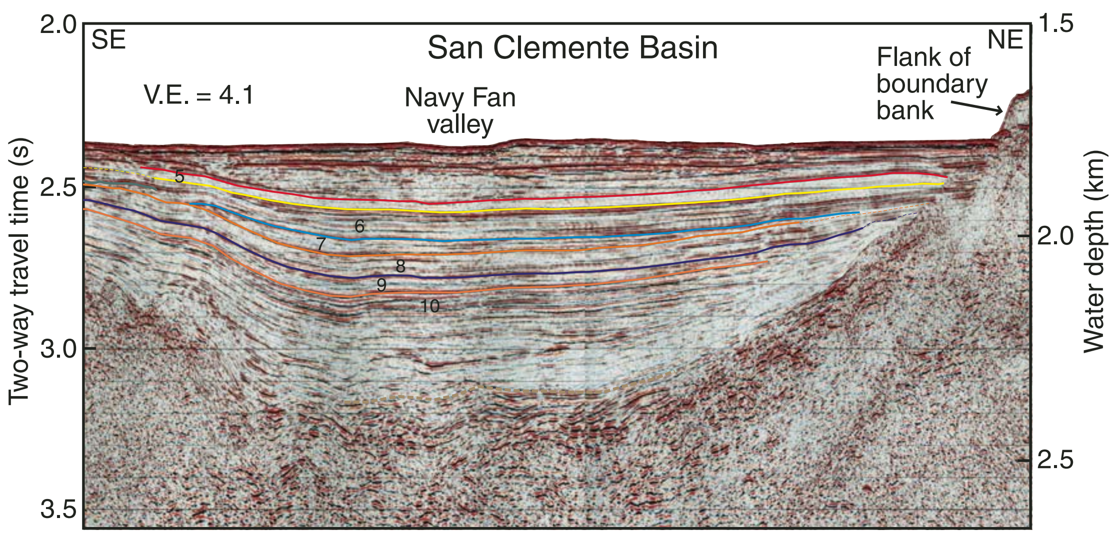


Figure 19. Seismic profile across northeastern Navy Fan showing interpreted seismic stratigraphy and oxygen isotope stages 5–10. Use of this profile is courtesy of M. Legg; location is shown in Figure 18. V.E.—Vertical exaggeration.

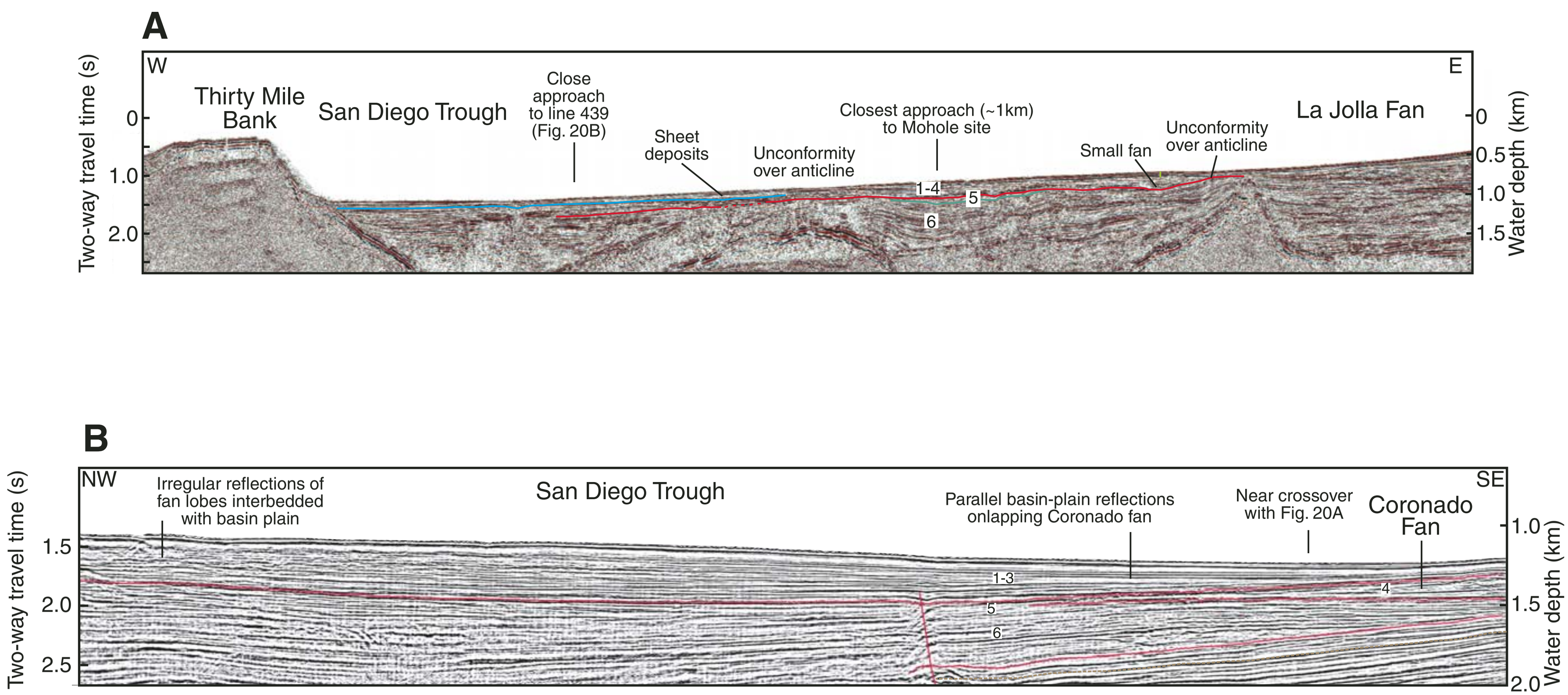


Figure 20. Seismic-reflection profiles from southern San Diego Trough. (A) Profile 446 showing the tie from the Mohole site to the floor of San Diego Trough and the behavior of reflectors across anticlines. (B) Axial profile 439 showing change in facies character along the Trough. Figure locations are shown in Figure 18.

lead to unconformities between lowstand packets where there is ongoing tectonic uplift, for example within San Clemente basin in Figure 19, and on low anticlines within San Diego Trough in Figure 20A.

Dated piston cores from Navy Fan (Piper and Normark, 1983) show that Navy Fan received only two small turbidity currents in the Holocene, probably initiated by seismically triggered slope failure in Coronado Canyon. This suggests that Holocene flows from La Jolla Fan do not reach Navy Fan. During the late Pleistocene (OIS 2), turbidites were abundant and coarse grained. The OIS 5 acoustically transparent unit and associated unconformities underlie 100–150 ms of turbidite sediment.

DISCUSSION

Sea-Level Change and Submarine Canyons

Figure 22 illustrates the major changes in sediment transport to the basins between lowstand, at ca. 25 ka, and the latest Holocene (ca. 1 ka). During lowstand, most inner basins were fed by one or more submarine canyons, which were the principal pathways for moving coarse sediment from the coastal rivers to the deep basins. In addition, basins received sediment from littoral sources through slope gullies (Fig. 22A). Santa Barbara Basin lacks a major canyon, but during lowstand, turbidity currents were generated from the western side of the Santa Clara delta (Marsaglia et al., 1995). Where the rivers carried sufficient sediment to form deltas, such as the Santa Clara delta and the shelf south of Long Beach, multiple canyon heads were formed probably in response to rapid lateral shifts of the river estuaries (see Figs. 6 and 13). During lowstand, the southern basins (Gulf of Santa Catalina and San Diego Trough) were open, i.e., sediment moved into the more seaward basins, Catalina and South San Clemente (Fig. 22A).

During highstand conditions, most slope gullies and about half of the submarine canyons were deprived of sediment because their heads were stranded on the upper slope or outer shelf (Fig. 22B). There were few Holocene turbidity currents generated that were capable of reaching Catalina Basin from the San Gabriel channel system in the eastern Gulf of Santa Catalina area or Navy Fan from the San Diego Trough and its contributory fan systems. Although Newport and La Jolla Canyons maintained some sediment supply to San Diego Trough, the rate of supply was not sufficient to create many turbidity currents capable of reaching San Clemente Basin (Piper and Normark, 1983). In this sense, all inner basins of the Borderland were "closed" during highstand conditions retaining most of the sediment delivered to the basins.

Two main factors influence how effective a particular canyon is as a pathway (Fig. 23):

(1) Whether the continental shelf is narrow (as north of La Jolla, or west of Point Dume) or wide (as offshore Los Angeles and San Diego). Where the shelf is wide,

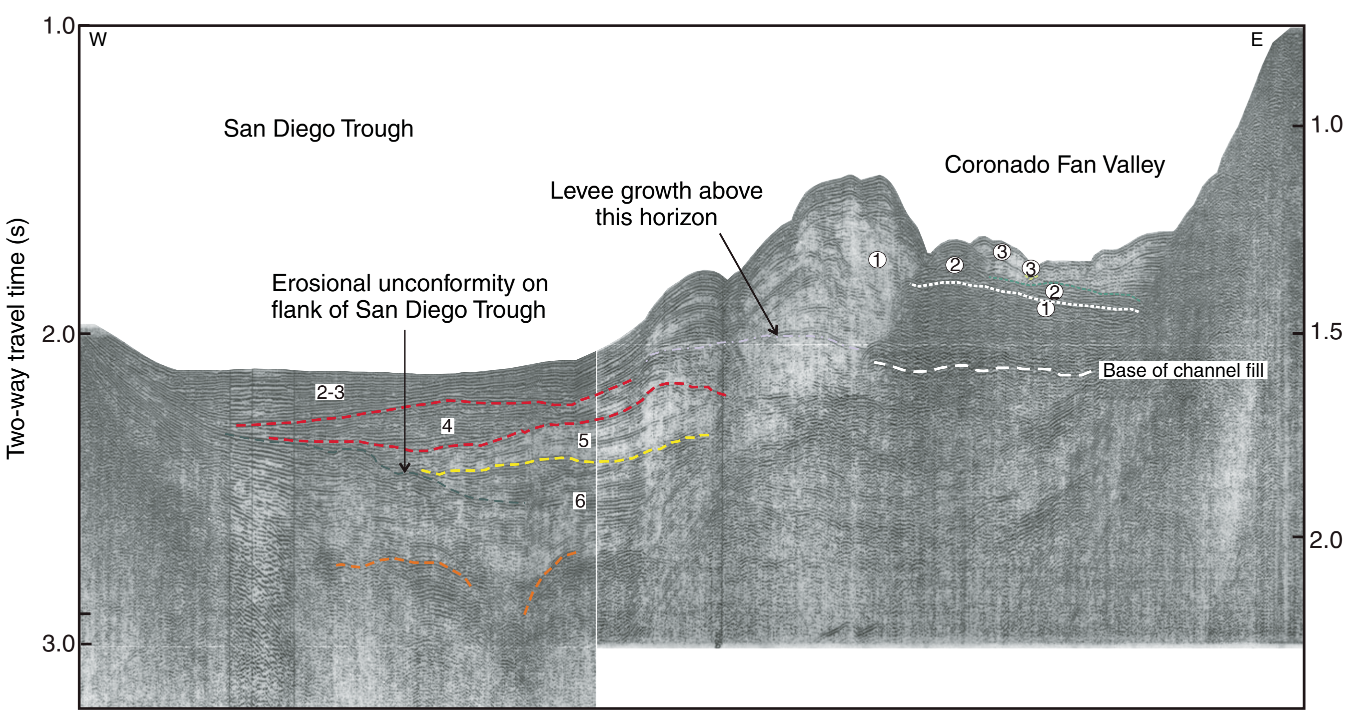
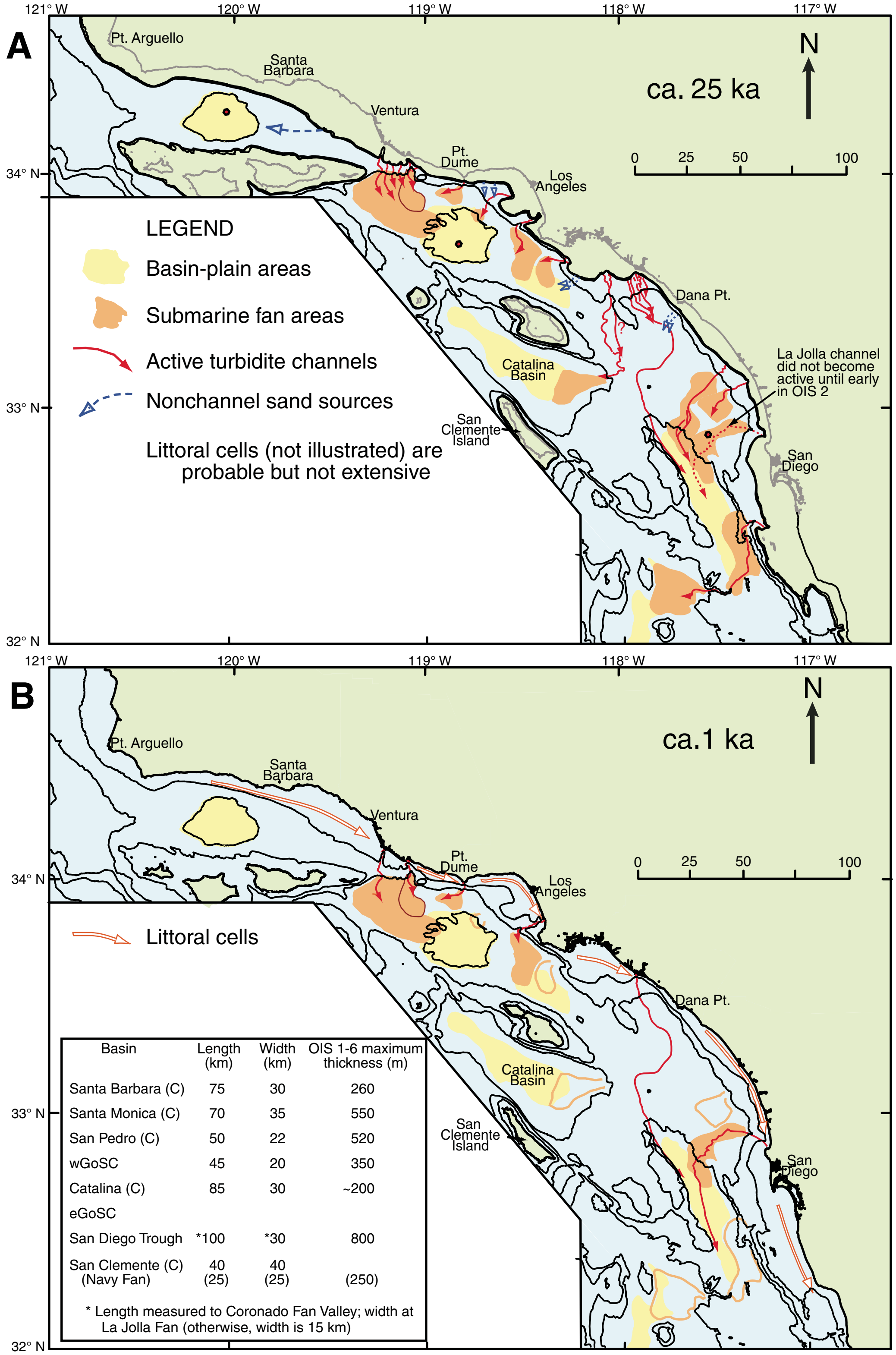


Figure 21. High-resolution, single-channel, air-gun profile Channel 6 line C (following designation of Smith and Normark, 1976) showing the architecture of Coronado Fan and the erosional surface on the western side of San Diego Trough. Stratigraphic interpretation shows oxygen isotope stages 2–6 in San Diego Trough; 3, 2, and 1 are successively smaller channels (on right) and corresponding levees (on left) on Coronado Fan discussed in text. Profile location is shown in Figure 18.



Basin	Length (km)	Width (km)	OIS 1-6 maximum thickness (m)
Santa Barbara (C)	75	30	260
Santa Monica (C)	70	35	550
San Pedro (C)	50	22	520
wGoSC	45	20	350
Catalina (C)	85	30	~200
eGoSC			
San Diego Trough	*100	*30	800
San Clemente (C) (Navy Fan)	40 (25)	40 (25)	(250)

* Length measured to Coronado Fan Valley; width at La Jolla Fan (otherwise, width is 15 km)

Figure 22. Schematic maps comparing relative sediment input for (A) late Quaternary (ca. 25 ka) and (B) latest Holocene (ca. 1 ka) for the inner basins of the Borderland. Basins noted with "(C)" are closed basins; the other basins are "open," but during highstand conditions, insufficient sediment supply results in little loss from these basins. Submarine fans that have been cut off from a source during the late Holocene are shown in outline only (B). The inset table gives basin dimensions and the interpreted maximum thickness of sediment fill during oxygen isotope stages 1 through 6 (see text). Basin dimensions approximated at 200 m above the basin fill. OIS—oxygen isotope stage. Contour intervals are 100 m, 500 m, and each successive 500-m interval (adapted from Fig. 1, which is based on Divins and Metzger, 2003).

canyons become stranded from their fluvial sediment sources at highstands of sea level, as in the case of Santa Monica Canyon (4 in Fig. 1) and Coronado Canyon (13 in Fig. 1), whereas on narrow shelves canyons tend to persist at highstands (for example, Hueneme Canyon—1; Mugu Canyon—2; Dume Canyon—3; and La Jolla Canyon—11 in Fig. 1).

(2) Whether a canyon is fed directly by a large river (for example, Hueneme and Coronado Canyons) or principally by longshore drift (for example, Dume and La Jolla Canyons). During rapid falls in sea level, rivers were incised across the shelf and thus discharged at one location throughout the lowstand, more efficiently transferring sediment directly into a broad fan valley. Only as sea level began to rise did a delta plain develop that fed down-drift beaches and canyons.

Thus there is a complex interplay between sea-level change and the input of sediment into the turbidite basins, that depends not only on the absolute level of the sea compared with coastal topography, but also on the rate of sea-level fall and rise in partitioning sediment between canyons and fan valleys seaward of river mouths and the down-drift beach systems that nourish canyons remote from river mouths. River-mouth canyons transport sand principally by hyperpycnal flows that deposit proximally on mid fans, whereas more turbulent flows generated by ignitive oceanographic flows in canyon heads efficiently transport sediment to the basin floors (Piper and Normark, 2001).

This study has shown the critical importance of submarine canyons in controlling the sediment dispersal patterns in the California Borderland. It is therefore necessary to consider the ways in which sea-level change interacts with canyons to either turn them off or switch them on. Subparallel slope gullies are common features on prodeltaic slopes (e.g., Chiocci and Normark, 1992; Field et al., 1999) and are seen in the Borderland seaward of or adjacent to lowstand deltas (e.g., Fig. 7, along the southern margin of the San Pedro shelf). There does not seem to be any correspondence between the position of most gullies and the position of distributary mouths (Piper et al., 1990). Seaward of rivers with hyperpycnal discharge there is commonly a canyon that leads across the slope to the river mouth (e.g., the Var Canyon, Mulder et al., 1998). Canyons remote from rivers appear to form where the interaction of coastal geomorphology with edge waves focuses rip currents during storms. A feedback process operates here, because rip currents preferentially occur where

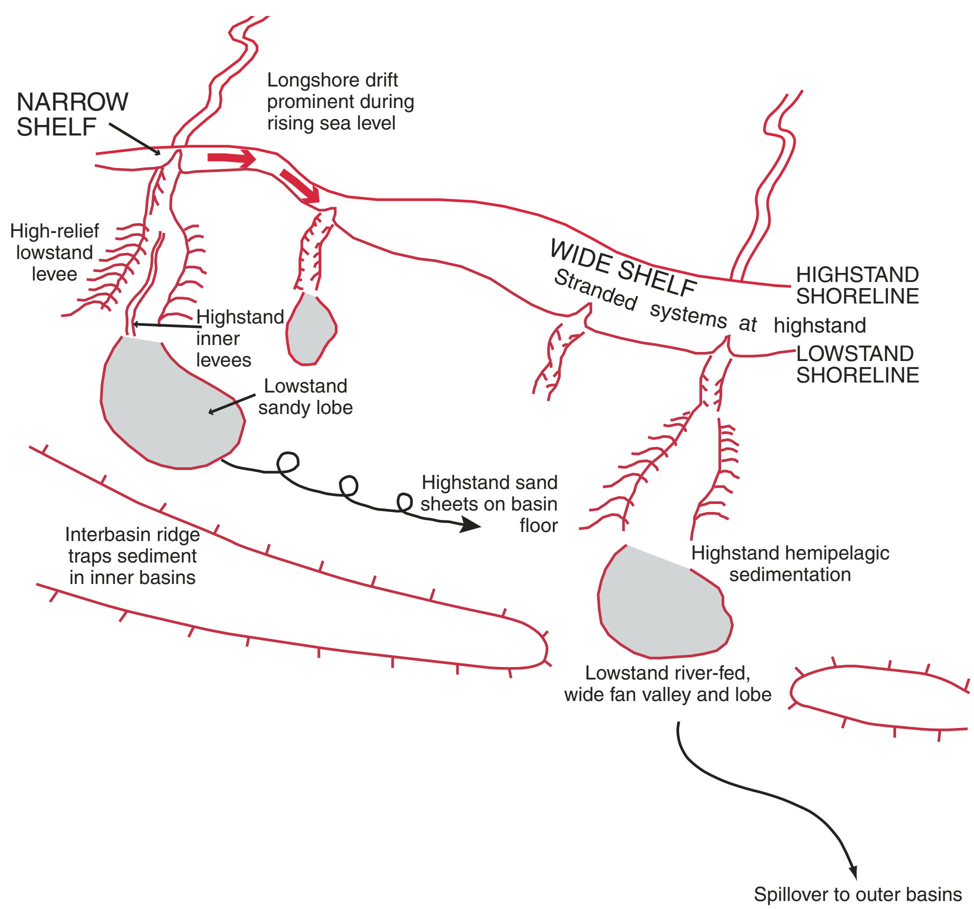


Figure 23. Cartoon summarizing the role of sea level and shelf width in influencing the style of turbidite deposition in the California Borderland.

there is a bathymetric depression across the surf zone. Canyon erosion and maintenance is largely the result of turbidity currents that transport significant amounts of sand: there is little evidence for significant erosion from muddy turbidity currents.

During rapid falls in sea level, delta distributaries become incised into earlier delta deposits, and the increased gradient favors the inertial flow of bedload in a hyperpycnal manner down the slope (as described by Prior and Bornhold, 1989). Such bedload flows favor canyon erosion. As a result, the accidental location of a delta distributary at the time that a sea-level fall begins will be very important in controlling where the major feeder canyon is located during a lowstand, e.g., Hueneme, Mugu, and Newport Canyons.

In the case of canyons fed by littoral drift, there is likely to be a tendency for old canyons to be reexcavated, as noted by Shepard and Dill (1966) for La Jolla Canyon. The old filled canyon is likely to be a slight bathymetric depression on the shelf, because of differential compaction of muddy sediment filling the canyon after abandonment. The fill can be reworked more readily than surrounding bedrock during storms, and the position of edge waves may remain constant. Sandy ignitive flows produced during storms in canyon heads (Fukushima et al., 1985) are also likely to be highly erosive. This mechanism suggests that a gradual fall in sea level will maintain a canyon in one position, but a rapid fall stands a greater chance of initiating a new canyon. Furthermore, extreme lowstands create situations in which stranded shelf-edge canyons can be reactivated.

Sediment Accumulations Post–160 ka

The basins in the California Borderland appear to have similar depositional histories for at least the past 200 ka. For Santa Barbara Basin this can be demonstrated by borehole data at ODP Site 893 and a recent piston coring program that extends the record at Site 893 back to more than 400 ka (Kennett, 1995; Nicholson et al., 2006). The rest of the basins discussed in this chapter lack borehole data older than 45 ka, but they share similar seismic-stratigraphic characteristics. Turbidite-fan facies of OIS 2-3 lowstand in Santa Monica Basin overlie an interval with reflection character indicative of hemipelagic sediment or muddy turbidite (Fig. 5A; Normark et al., 2006a). This relatively draping interval in turn overlies a thicker sequence with turbidite fan character. Similar seismic-stratigraphic signatures are found in San Pedro, Catalina, and San Clemente Basins as well as San Diego Trough (Figs. 11, 19, 20, and 21) regardless of the type of seismic-reflection data available.

Extrapolation of available sediment dates (ODP 1015 and Mohole sites together with some piston-core sites, Normark et al., this volume, Chapter 2.6) shows that the deeper interval of turbidite-fan signatures is consistent with deposition during OIS 6. For purposes of comparison, the inset table in Figure 22B shows basin dimensions and the maximum thickness of sediment accumulated after OIS 7. To standardize estimates, the dimensions listed are taken from basin-slope depths that are ~200 m above the deepest part of the basin. Santa Monica and San Pedro Basins have similar maximum thicknesses, but the small size of San Pedro Basin shows that it receives much less sediment than the delta-fed Santa Monica Basin. The greatest thickness is seen locally in San Diego Trough, which probably reflects its narrowness and the fact that it is fed by all canyons and slope gullies between Newport and La Jolla Canyons.

CONCLUSIONS

Most of the inner basins of the continental Borderland continue to receive sediment as a result of turbidity-current activity during the present sea-level highstand. Half of the major submarine canyons, notably Hueneme, Redondo, Newport, and La Jolla, have remained active conduits in the Holocene by intercepting sand moving in the littoral cells; Hueneme is also fed by floods from the Santa Clara delta. During the OIS 2-1 transgression, several of the canyons were shut off as sea level rose, e.g., Oceanside, so that others farther downcurrent in the littoral cell benefited from high rates of sediment input, for example, La Jolla. In the Santa Monica Basin during the transgression, relatively high rates of sedimentation occurred on Mugu and Dume fans, as a result of distributary switching and southward littoral drift on the Santa Clara delta. The distribution of turbidite sedimentation within the offshore basins is controlled by sea-level state, which affects not only the rate of supply of coarse sediment but also which canyons remain (or become more) active during sea-level rise. While the inner basins remain active during highstand, the sediment supply is generally reduced sufficiently that little coarse sediment is transported to the basins farther west. The pattern of sedimentation seen during the OIS 6 lowstand is similar to that documented for OIS 2.

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