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Postglacial sedimentary record of the Southern California continental shelf and slope, Point Conception to Dana Point

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ABSTRACT

Sedimentary strata on the Southern California shelf and slope (Point Conception to Dana Point) display patterns and rates of sediment accumulation that convey information on sea-level inundation, sediment supply, and oceanic transport processes following the Last Glacial Maximum. In Santa Monica Bay and San Pedro Bay, postglacial transgression is recorded in shelf deposits by wave-ravinement surfaces dated at 13–11 ka and an upsection transition from coastal to shallow-marine sediment facies. Depositional conditions analogous to the modern environment were established in the bays by 8–9 ka. On the continental slope, transgression is evidenced in places by an increase in sediment grain size and accumulation rate ca. 15–10 ka, a consequence of coastal ravinement and downslope resedimentation, perhaps in conjunction with climatic increases in fluvial sediment delivery. Grain sizes and accumulation rates then decreased after 12–10 ka when the shelf flooded and backfilled under rising sea level. The Santa Barbara coastal cell contains the largest mass of postglacial sediment at 32–42 × 10^9 metric tons, most of which occurs between offshore Santa Barbara and Hueneme Canyon. The San Pedro cell contains the second largest quantity of sediment, 8–11 × 10^9 metric tons, much of which is present on the eastern Palos Verdes and outer San Pedro shelves. By comparison, the mass of sediment sequestered within the Santa Monica cell is smaller at ~6–8 × 10^9 metric tons. The postglacial sediment mass distribution among coastal cells reflects the size of local fluvial sediment sources, whereas intracell accumulation patterns reflect antecedent bathymetric features conducive for sediment bypass or trapping.

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INTRODUCTION

At the interface between land and the deep ocean, continental margin strata form by a diverse range of sedimentary processes and thus archive climatic, hydrologic, and oceanic phenomena that affect life at the coast. Learning how to read this record is a standing priority in the coastal and marine geosciences, an endeavor that extends from the pioneering work of F.P. Shepard and K.O. Emery in the sea off Southern California (Shepard and Emery, 1941; Emery and Shepard, 1945). Today, characterizing the magnitude and variability of land-to-ocean sediment delivery and accumulation is a topic of vigorous research worldwide. Motivated by issues of marine environmental quality, geologic hazards, and climate change, geoscientists seek a general understanding of natural and anthropogenic influences on coastal and marine systems. The period following the Last Glacial Maximum (LGM) (18–20 ka) was particularly influential on margins, because shelves and coastal plains were impacted by continental runoff intensified by pluvials and glacial meltwater in addition to rapidly rising eustatic sea level. Geologic records of the profound environmental changes that took place during deglacial and postglacial times provide a perspective for understanding effects of natural and anthropogenic influences on coastal and marine sedimentation during historical times.

This paper examines the sediment-accumulation history of mainland shelf and slope deposits off Southern California (Fig. 1), with special emphasis placed on the margin's response to transgression following the LGM. Building on previous research in the region, we present an interpretation of marine sedimentation in the face of rising sea level, variations in fluvial sediment delivery, and coastal ocean processes. Following the source-to-sink theme of this Special Paper, we examine across-shelf sediment movement on millennial timescales from the perspective of shelf and slope sediment archives. Salient background on the regional tectonic framework, coastal oceanography, and modern sediment dispersal is provided by Fisher et al. (this volume, Chapter 4.2), Noble et al. (this volume, Chapter 3.3), and Warrick and Farnsworth (this volume, Chapters 2.2 and 2.3), respectively, and a complementary study of late Quaternary sediment accumulation in Southern California Borderland basins is presented by Normark et al. (this volume, Chapter 2.6).

BACKGROUND

Transgressive Sedimentation on Margins

Contemporary concepts in marine sedimentology and stratigraphy are used throughout this paper to interpret sedimentary records of the Southern California shelf and slope, so a

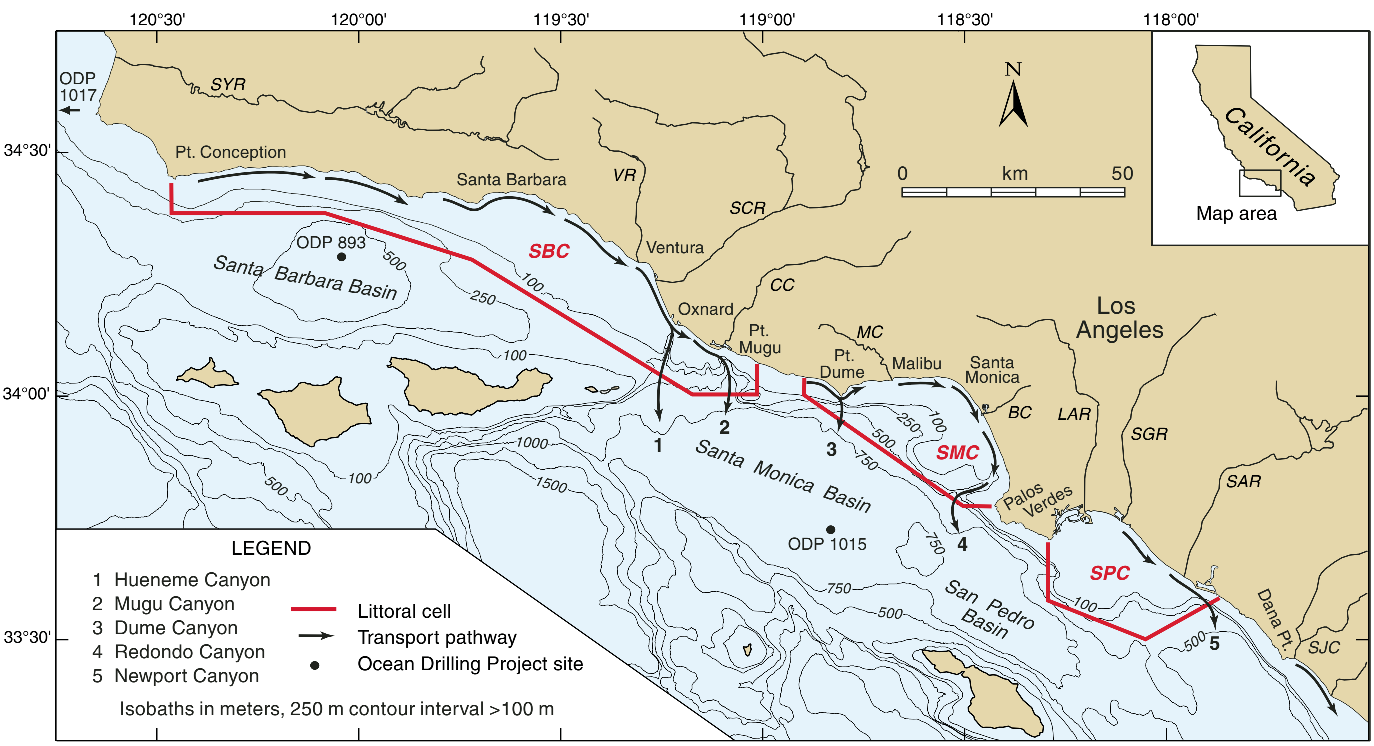

Figure 1. Bathymetric map of the Southern California margin showing littoral sediment-transport pathways of the Santa Barbara (SBC), Santa Monica (SMC), and San Pedro coastal cells (after Brownlie and Taylor, 1981). Abbreviations: BC—Ballona Creek; CC—Calleguas Creek; LAR—Los Angeles River; MC—Malibu Creek; SAR—Santa Ana River; SCR—Santa Clara River; SGR—San Gabriel River; SJC—San Jose Creek; SYR—Santa Ynez River; VR—Ventura River.

brief review is in order. The regime model of Swift and Thorne (1991) and the sequence-stratigraphic model originally proposed by Posamentier and Vail (1988) are by far the most flexible and widely cited conceptual models of eustatically forced shelf sedimentation. The regime model employs a sediment continuity relationship involving four master variables: (1) rate of base-level rise (*R*); (2) rate of sediment transport (*D*); (3) rate of sediment supply (*Q*); and (4) a sediment textural factor (*M*). The ratio of *R* and *D* (accommodation variables) and *Q* and *M* (supply variables) determine where a particular shelf system falls between the accommodation- and supply-dominated regime types. Supply-dominated regimes are widespread on tectonically active margins with narrow or nonexistent coastal plains and shelves, properties that promote river-mouth bypass, oceanic sediment dispersal, and allochthonous sedimentation on the shelf and slope. Supply-dominated shelves are also associated with major river deltas—the relative size of the regime variables rather than their absolute magnitude is what determines whether a particular system is supply or accommodation dominated. In contrast, accommodation-dominated shelves are common on modern passive margins where terrigenous sediment accumulation has yet to fill broad coastal plains and valleys flooded by postglacial sea-level rise. Such shelves are generally sediment starved, because most (if not all) of the fine-grained sediment eroded from the continent becomes entrapped within estuaries and lagoons landward of the shoreline. Consequently, the greater proportion of lithogenic sediment transported within these regimes is autochthonous in origin, produced by shallow-marine erosion of the shoreface and shelf seafloor (Swift and Thorne, 1991). An interesting feature of the Southern California shelf is that *both* types of regimes exist contemporaneously and in close proximity, in part, because of tectonically produced topography that segments the coast into cells with discrete sediment sources and sinks.

The response to transgression—shoreline migration landward and upward in space and time—is not fundamentally different between supply- and accommodation-dominated shelf regimes. Local factors, including physiography, subsidence, eustacy, and sediment flux, determine the location, geometry, and stratigraphic architecture of transgressive-highstand sediment prisms (Posamentier and Vail, 1988; Posamentier and Allen, 1993; Cattaneo and Steel, 2003). The rate of sea-level rise and the gradient of the flooded shelf and coastal plain (where present) determine the rate of shoreline retreat by transgressive ravinement, i.e., shoreface erosion by breaking waves (Nummedal and Swift, 1988). In general, steady sea-level rise on gentle slopes (<0.001) favors preservation of transgressive and underlying strata, whereas steep slopes (>0.001) promote ravinement and destruction of coastal strata. In reality, interplay among eustatic sea-level rise, wave climate, subsidence, and antecedent topography created by paleovalleys enhances stratal preservation during transgression, and as a general rule preservation is best in the lowest portion of the coastal sequence (Belknap and Kraft, 1985). In some areas of the Southern California shelf, preservation of transgressive strata can depend almost exclusively on vertical accommodation space imparted by antecedent topography (Osborne et al., 1980).

Incised valley-fill sequences can provide detailed transgressive stratigraphy and essential context regarding shelf sedimentation in the face of sea-level rise and shoreline retreat. The generic sequence is remarkably similar among a wide range of channel types, from small tidal creeks to large coastal plain estuaries (Nummedal and Swift, 1988; Dalrymple et al., 1992). There are four distinctive surfaces in a classical transgressive sequence, from bottom to top: (1) the sequence boundary; (2) the transgressive surface; (3) the tidal ravinement surface; and (4) the wave-ravinement surface (see examples in Fig. 2). The sequence boundary, an erosional surface created by river incision during base-level fall, separates underlying regressive coastal strata and overlying lowstand fluvial deposits. Above this boundary is the transgressive surface, a conformable facies transition marking the onset of marine flooding, and transition from lowstand fluvial to transgressive estuarine deposition. With continued shoreline retreat, much of the estuarine strata emplaced within valleys is subsequently eroded by tidal currents, perhaps mantled by sand transported landward from the coast, and the erosional contact so formed is known as the tidal ravinement surface. Should a barrier migrate across the estuary mouth, shoreline erosion has potential to add a wave ravinement surface to the transgressive sequence. As is the case on nonembayed coasts, the preservation potential of channel-fill sequences varies with intensity of ravinement as influenced by coastal topography, rate of sea-level rise, wave energy, among other factors (Belknap and Kraft, 1985). Although there are no general rules regarding the maximum depth of tide and wave ravinement, observations from a wide range of Holocene shelves suggest a range of ~10–20 m (Saito, 1994).

One consequence of transgression is formation of "healing phase" deposits on the continental slope, strata created through resedimentation of material eroded from the shelf seafloor, and retreating shoreface (Posamentier and Allen, 1993). Healing-phase deposits are well developed on ramp margins whose shelves are narrow and thus incapable of trapping large quantities of terrigenous sediment, such as shelves off Southern California. Significantly, because healing phase deposits are emplaced well below wave base, they have potential to provide a continental slope record of transgressive processes occurring landward of the shelf edge. Healing-phase deposits tend to be stratigraphically condensed compared to coeval submarine fan sequences, which tend to form through episodic turbidite deposition.

The Southern California Shelf and Slope

Coastal Cells and Provinces

Shoreline embayments between Point Conception and Dana Point form a series of coastal cells within which sediment is transported by littoral drift to shelf, canyon, and basin sinks. The three major cells in the study area are (1) the Santa Barbara cell, (2) the Santa Monica cell, and (3) the San Pedro cell (Fig. 1). Although there is some leakage of coastal sand between contiguous cells, the embayments constitute discrete sediment dispersal systems for material transported as bedload. In contrast, fine-grained material transported in suspension can move between cells, and evidence of intercell transport includes remotely sensed surface plumes (Mertes and Warrick, 2001), clay mineral provenance (Hein et al., 2003), and patterns of contaminated seafloor sediments (Lee and Wiberg, 2002; Sommerfield and Lee, 2003). In support of these observations, exchange of water and suspended matter between the Santa Monica and San Pedro coastal cells is predicted by regional hydrodynamic and sediment-transport models (Blaas et al., 2006).

Using a comprehensive, multibeam bathymetric data set, Gardner et al. (2003) and Bohannon et al. (2004) subdivided the Southern California margin into distinct provinces on the basis of water depth and seafloor gradient. This systemization, which is convenient for describing sediment-accumulation patterns on the margin, is used in this paper to organize the various observations. The distribution of provinces is as follows: (1) shelf

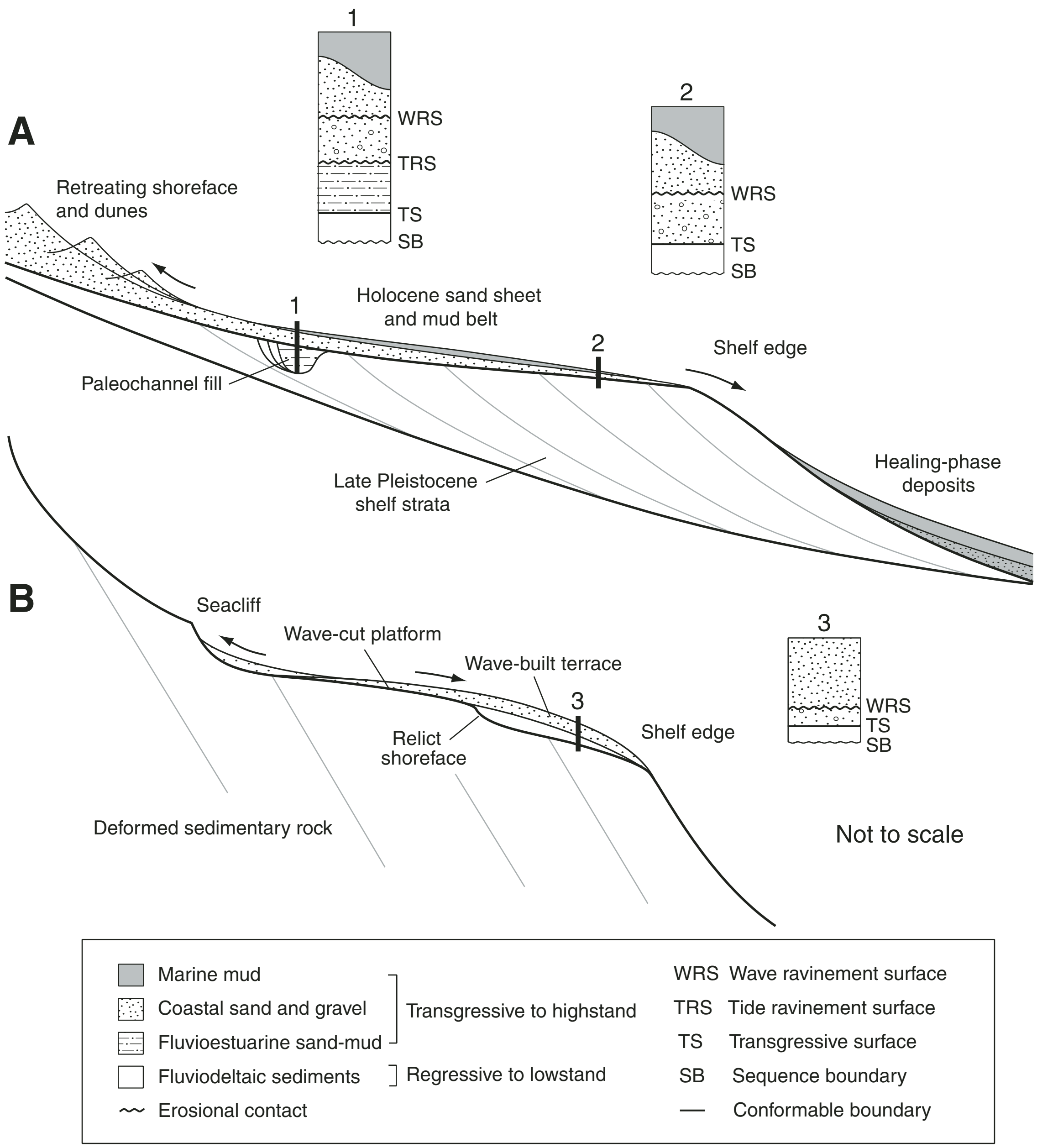

Figure 2. Generalized geometry and stratigraphy of Southern California shelves: (A) accretionary shelves seaward of coastal valleys; and (B) wave-cut platforms and shelf terraces off sea cliff coasts. Accretionary and terraced shelf subtypes are consistent with the supply-dominated and accommodation-dominated, end-member types discussed in the text. See text for an interpretation of the stratigraphic sequences.

province (0–100 m water depths, <0.5° gradients); (2) marginal plateau province (consisting of rock outcrops, 50–100 m, <0.5°); (3) submarine canyon province (60–800 m, >1.5°); (4) basin slope province (100–750 m, 11°–14°); (5) apron province (80–800 m, 1°–2°); and (6) basin province (750–850 m, <2°).

The Southern California shelf province consists of two subtypes: (1) low- to intermediate-gradient (0.0015), supply-dominated shelves with small delta plains; and (2) high-gradient (0.018), accommodation-dominated shelves backed by coastal bluffs or sea cliffs. The supply-dominated shelves are for the most part accretionary and composed of fluvial and coastal sediment prisms emplaced during the late Pleistocene and Holocene. Conversely, the accommodation-dominated shelves are nondepositional and consist of a wave-cut platform and wave-built terrace, thinly mantled by late Pleistocene and Holocene sediments. In places, these sediments unconformably overly deformed and uplifted Miocene sedimentary rock (Moore, 1969; Bohannon et al., 2004). Supply-dominated shelf segments are associated with coastal plains drained by the Ventura and Santa Clara rivers, Ballona Creek, and the Los Angeles River (see Fig. 1 for locations). Most of the intervening areas are accommodation dominated, with sediment sourced from local shoreface erosion, bluff erosion, and numerous coastal drainages.

Postglacial Sedimentology and Stratigraphy

Dupré et al. (1991) developed a conceptual model of tectonically influenced coastal sedimentation that is instructive for understanding relationships between relict landforms of the Southern California shelf and stratal preservation. This model specifies that tectonically uplifting areas develop wave-cut cliffs and platforms when the rate of uplift equals or exceeds that of eustatic sea-level rise. Wave-formed terraces are erosional notches mantled by thin wedges of transgressive sediment (see Fig. 2). In contrast, stable or subsiding areas constitute topographic lows and create pathways for continental drainage. The stratigraphic record within these areas is characterized by an upward succession of fluvial sediment deposited during times of falling sea level and lowstands, followed by estuarine-marine sediments emplaced during transgression. Hence, the potential to create thick, stratigraphically complete sequences is highest over subsiding areas, fluvially entrenched valleys, and proximal basins with sufficient accommodation space.

Despite the large number of rivers that drain the Southern California coast, Quaternary paleochannels and drainage networks are poorly preserved on the adjoining shelf. Transgressive ravinement over steep coastal topography can explain the spotty occurrence of buried channels (e.g., Anima et al., 2002). Previous seismic-reflection and echo-sounding studies have resolved segments of buried channels between shelf-indenting canyon heads and the mouths of larger rivers, confirming that they indeed extended their courses to the shelf edge during the LGM. However, many of the smaller rivers may have existed as non-incising alluvial bypass systems (e.g., Posamentier, 2001) whose channels were completely eroded during the postglacial transgression. As discussed later in this paper, the hydraulic geometry of preserved paleochannels suggests that the ancestral rivers carried much more water and suspended sediment than their modern counterparts.

Compressional and extensional folding and faulting are known to influence patterns of Quaternary sedimentation on the Southern California shelf and slope (Bohannon et al., 2004). A well-documented example of tectonic changes in sediment dispersal pathways is late Quaternary tilting of the Ventura shelf (Dahlen et al., 1990), which diverted littoral drift from Santa Barbara Basin to Santa Monica Basin (Normark et al., 1998). Geochronology of subaerial marine terraces indicates that much of the Southern California coast is emerging at rates of 0.02 mm/yr to 10 mm/yr, averaged over the past 12.5×10^3 years (see references in Gornitz et al., 1997). Between Point Conception and Point Dume, uplift rates are on the high end at 0.4–10 mm/yr, whereas lower rates of 0.02–0.7 mm/yr occur between Point Dume and Point Loma (Gornitz et al., 1997). Despite influences of tectonism in the region, most workers concur that the latest Pleistocene and Holocene stratigraphy of the shelf and slope is largely eustatic in origin (Birkeland, 1972; Osborne et al., 1980; Nardin, 1983; Sommerfield and Lee, 2003).

Generic transgressive sequences for Southern California shelves are depicted in Figure 2. At the sequence base, the lowstand surface of erosion cuts into regressive strata, which are typically coastal or deltaic in origin. This surface is an unconformable boundary between lowstand and transgressive sedimentary regimes. Next upsection is the ravinement surface, produced by shoreface erosion under breaking waves as the shoreline migrates landward and upward with rising sea level. Left behind is an onlapping wedge or sheet of coarse-grained sediment typically composed of amalgamated beach sand, gravel, and reworked shell debris. The sand sheet may extend across the full width of the shelf, perhaps becoming amalgamated with modern coastal sands and relict Pleistocene sediments at its landward and seaward limits, respectively. A product of shoreface and shelf ravinement, coeval healing-phase deposits are present on the upper continental slope (Fig. 2), onlapping regressive or lowstand strata. Seaward of accommodation-dominated shelves, healing-phase sands may be capped by allochthonous marine mud derived from fluvial and coastal erosional sources. On supply-dominated shelves the transgressive unit may be capped by late transgressive-highstand marine muds that coalesce into a continuous blanket or mud belt (e.g., Grossman et al., 2006). In general, high rates of postglacial sediment accumulation in mud-belt areas promote stratal expansion, whereas low to negligible rates form condensed sections, most conspicuously at the shelf edge.

Oceanographic observations off Southern California indicate that wave base varies along-coast in accord with coastal topography and wind-wave climatology (see Xu and Noble, this volume, Chapter 3.2). Fair-weather wave base (<2 m significant wave height) in summer is typically shallower than 20 m water depth, whereas average winter storm waves 2–4 m in height are capable of resuspending fine-grained sediments in 35–70 m water depths

(Wiberg et al., 2002; Noble and Xu, 2003). Such waves have a recurrence interval of one to two years, placing the entire inner to middle shelf at or above wave base on an annual basis. By contrast, storm waves 6–7 m in height have a 10-yr recurrence interval and generate orbital flows sufficient to entrain medium-grained sands across the full width of the shelf (e.g., Wiberg et al., 2002). The Southern California Borderland is partly sheltered from northwesterly swell and storm waves generated in the north Pacific, an effect that increases with distance southeast of Point Conception. As a consequence, the Santa Barbara coastal cell is significantly more energetic than the downwind Santa Monica and San Pedro cells.

Although there have been attempts to reconstruct postglacial sea levels on the Southern California margin, only a general sea-level history is known from the inferred ages of submerged (relict) wave-cut terraces (Osborne et al., 1980; Nardin et al., 1981; Slater et al., 2002; also see Fig. 3). The Southern California margin falls within the latitudinal zone expected to have experienced Holocene sea levels that were several meters higher than at present because of hydro-isostatic loading and crustal displacement (Fleming et al., 1998). Evidence of this effect has yet to be reported for the margin, but the narrow shelf probably limited the extent of hydro-isostasy in the first place (e.g., Peltier, 2002). Tide gauge records for coastal stations at Santa Monica, Los Angeles, and Newport Beach indicate rates of relative sea-level rise (in mm/yr) of 1.59 ± 0.25, 0.84 ± 0.16, and 2.22 ± 0.53,

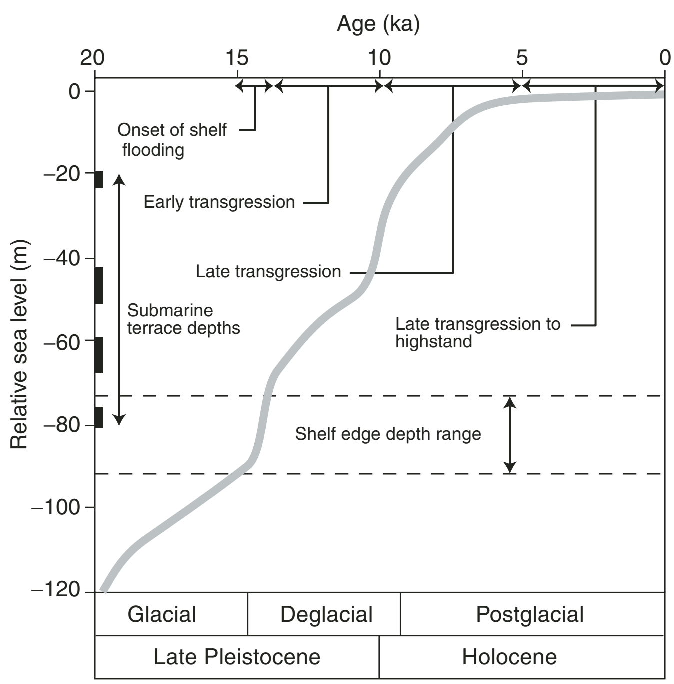

Figure 3. Postglacial eustatic sea-level curve of Fleming et al. (1998) with stages of shelf transgression noted for reference. Also shown are depth ranges of submerged wave-cut terraces interpreted to have formed by coastal erosion during brief stillstands in sea level (data from Slater et al., 2002).

respectively, averaged over the past four to seven decades (National Ocean Service, 2007). These rates bracket the 1–2 mm/yr eustatic mean (Fleming et al., 1998), and local departures from this mean are most likely a consequence of along-coast variations in uplift and subsidence.

Previous Work on Postglacial Sedimentation

Previous geological research on the Southern California margin has provided a firm understanding of late Quaternary depositional processes and systems (reviewed by Gorsline, 1992). However, not until recently were the appropriate data available to interpret the most recent stratigraphy in terms of eustacy, tectonics, variations in continental runoff, and coastal ocean processes. The spatial distribution of late Quaternary shelf successions is known from sediment thickness (isopach) maps developed from high-resolution (3.5 kHz), seismic-reflection surveys conducted in support of resource assessments and academic research (Osborne et al., 1980; Fischer et al., 1983; Dahlen et al., 1990; Hampton et al., 2002; Wolf and Gutmacher, 2004). Slater et al. (2002) synthesized data reported in earlier works and offered a postglacial sediment budget for the shelf. For the area considered in the present study, Point Conception to Dana Point, they estimated a total sediment volume of ~30 km^3. Here it is important to point out that in all previous work the base of the Holocene sediment prism was taken as the depth of a basal, regionally traceable seismic reflector of inferred age. In reality, this reflector could represent a lowstand surface of erosion *or* a transgressive ravinement surface with ages ranging from 18 ka (late Pleistocene) to 10 ka (early Holocene). The ^{14}C age dates of strata that correlate with the basal seismic reflector in Santa Monica Bay and San Pedro Bay fall within 10–13 cal. (calibrated) yr B.P. (McNeilan et al., 1996; Sommerfield and Lee, 2003; Sommerfield and Lee, 2004), providing some support for age inferences made in prior work.

For the Southern California Borderland basins, Schwalbach and Gorsline (1985) developed Holocene sediment budgets using seismically mapped sediment thicknesses and estimates of sediment delivery from coastal rivers. For the Santa Barbara, Santa Monica, and San Pedro Basins, they reported a sediment mass of 4.1×10^{10} metric tons (dry weight basis) averaged over the past 10 ka. By comparison, the open slope contains an estimated 1×10^{10} metric tons of Holocene sediment (Schwalbach and Gorsline, 1985). The volume of Holocene shelf sediment reported by Slater et al. (2002) when converted to dry sediment mass (assuming dry-bulk densities of 1500–2000 kg/m^3 measured by Sommerfield and Lee, 2003) is ~$4.5–6 \times 10^{10}$ metric tons. The shelf, slope, and basin sediment distribution implies that most of the fluvial sediment supplied to the coast rapidly transits the shelf and slope to permanent sinks in the borderland basins. The dispersive nature of the Southern California shelf is typical for U.S. Pacific shelves, which because of their narrowness and energy level trap only a fraction of the terrigenous sediment influx (Wheatcroft and Sommerfield, 2005).

The broader question of how and when the terrigenous supply is partitioned among shelf, slope, and basin environments has been considered by a number of workers. Using a comprehensive set of high-resolution, seismic-reflection data, Moore (1969) concluded that elevated stream discharge during the late Pleistocene was the primary source of canyon incision and sediment supply to the slope and basins. Further, he proposed that dilute sediment gravity flows generated on the shelf are the main mechanism of downslope transport, and that feeder submarine canyon and gullies systems are responsible for thick turbidite sequences present on the basin floors. In dated piston cores from Tanner Basin, Gorsline et al. (1968) noted a decrease in the quantity of terrigenous sediment buried after ca. 7.5 ka, postulating that this was a response to reduced stream gradients and increased trapping of sediment near the coast as shelves submerged under rising sea level. Nardin (1983) advanced these early ideas with a conceptual model of eustatically forced sedimentation that was rooted in concepts of passive-margin sequence stratigraphy. He proposed that basin sedimentation rates were highest during times of falling sea level, intermediate during sea-level lowstands and highstands, and lowest during transgression. This model specifies that falling sea level elicits maximum accumulation rates in basins, because shelf-to-basin sediment supply is enhanced by fluvial incision, and also because rivers discharge closer to the shelf edge and slope. Rising sea level counters this trend by reducing land-ocean hydraulic gradients, thereby decreasing the sediment-transport competence of coastal rivers.

Exceptions to the general lowstand-highstand sedimentation model are indicated for the Central and Southern California margin where interactions between relative sea level, transgressive ravinement, and antecedent topography led to high rates of sediment accumulation during postglacial times (Sommerfield and Lee, 2004; Grossman et al., 2006; Covault et al., 2007). Detailed geochronological studies of cores from the slope and inner basins off Southern California reveal that maximal rates of sediment accumulation occurred during the deglacial interval at some sites, the postglacial interval at others (Sommerfield and Lee, 2004; Normark and McGann, 2004; Normark et al., 2006; Normark et al., this volume, Chapter 2.6). For example, Sommerfield and Lee (2004) found that sediment mass accumulation rates at Santa Lucia Bank (Ocean Drilling Project [ODP] Site 1017), in Santa Barbara Basin (ODP Site 893), in Santa Monica Bay were maximal between 15 and 10 ka, *after* the LGM, decreasing significantly during the Holocene. They attributed the deceleration to the onset of transgressive sedimentation on the shelf, followed by increased sediment trapping landward of the shelf edge. In contrast, Normark and McGann (2004) found that linear sediment-accumulation rates in Santa Monica Basin (ODP Site 1015) remained high from 22 to 8 ka, spanning the period of rapid sea-level rise following the LGM. As elaborated later, differences in sediment-accumulation history among margin depositional sites can be reconciled in terms of local basin factors.

METHODS

High-resolution, seismic-reflection profiles and sediment cores were obtained for the present and related studies during five research cruises conducted between 1997 and 2002 by the U.S. Geological Survey. These cruises were designed to obtain data relevant to the identification of potential earthquake hazards presented by faults and landslides in the offshore Southern California region; another focus was to characterize sedimentary processes in coastal waters off Los Angeles in an effort to understand the fate of sediment-borne contaminants (see Lee and Wiberg, 2002, and Dojiri et al., 2003, for background). Cruise tracklines, ship operations, and details regarding seismic data acquisition and processing are detailed in a series of U.S. Geological Survey reports (Normark et al., 1999a, 1999b; Gutmacher et al., 2000; Normark et al., 2003). For correlating shallow, subbottom stratigraphy with down-core sedimentary records we used seismic-reflection data obtained with deep-towed Huntec boomer and standard 3.5 kHz systems, both of which provided a nominal vertical resolution of ~0.4 m. Standard piston cores and vibracores sited along these seismic lines were collected for sedimentological and chronological studies.

Methods of sediment coring, sedimentological analyses, and ^{14}C dating are detailed in Sommerfield and Lee (2003). Briefly, 33 standard piston cores and 30 electro-percussive vibracores were collected during research cruises in 1997 (S297SC) and 1999 (O299SC). Locations of cores selected for detailed sedimentological and chronological studies are shown in Figure 4. Aboard ship, cores were analyzed nondestructively for gamma-ray density, compressional wave velocity, and magnetic susceptibility using a multi-sensor core logger. In the laboratory, cores were split lengthwise, X-radiographed, and subsampled for grain-size analysis following standard sieving and SediGraph methods. Sedimentological and physical properties data were used to describe down-core lithology, compute acoustic impedance for correlation with high-resolution, seismic-reflection profiles, and to generate profiles of sediment bulk density for determination of mass accumulation rates. Lithofacies where described based on sediment textural data, and environment of deposition was inferred from depth-specific foraminifera (identified and counted by R. Boettcher, Micropaleo Consultants). Specimens of articulated bivalves and foraminifera were picked from cores by Micropaleo Consultants for ^{14}C age dating, which was performed at the National Ocean Science Accelerator Mass Spectrometry Facility in Woods Hole, Massachusetts. The ^{14}C dates not previously reported in Sommerfield and Lee (2003) or Sommerfield and Lee (2004) are listed in Table 1.

To delineate the spatial distribution of postglacial sediments on the shelf and uppermost slope, a sediment thickness (isopach) map was constructed by combining previously reported thickness data with new measurements made from high-resolution, seismic-reflection profiles collected for this study. Thickness data from Greene et al. (1978), Clarke et al. (1983), Fischer et al. (1983), Dahlen et al. (1990), and Hampton et al. (2002)

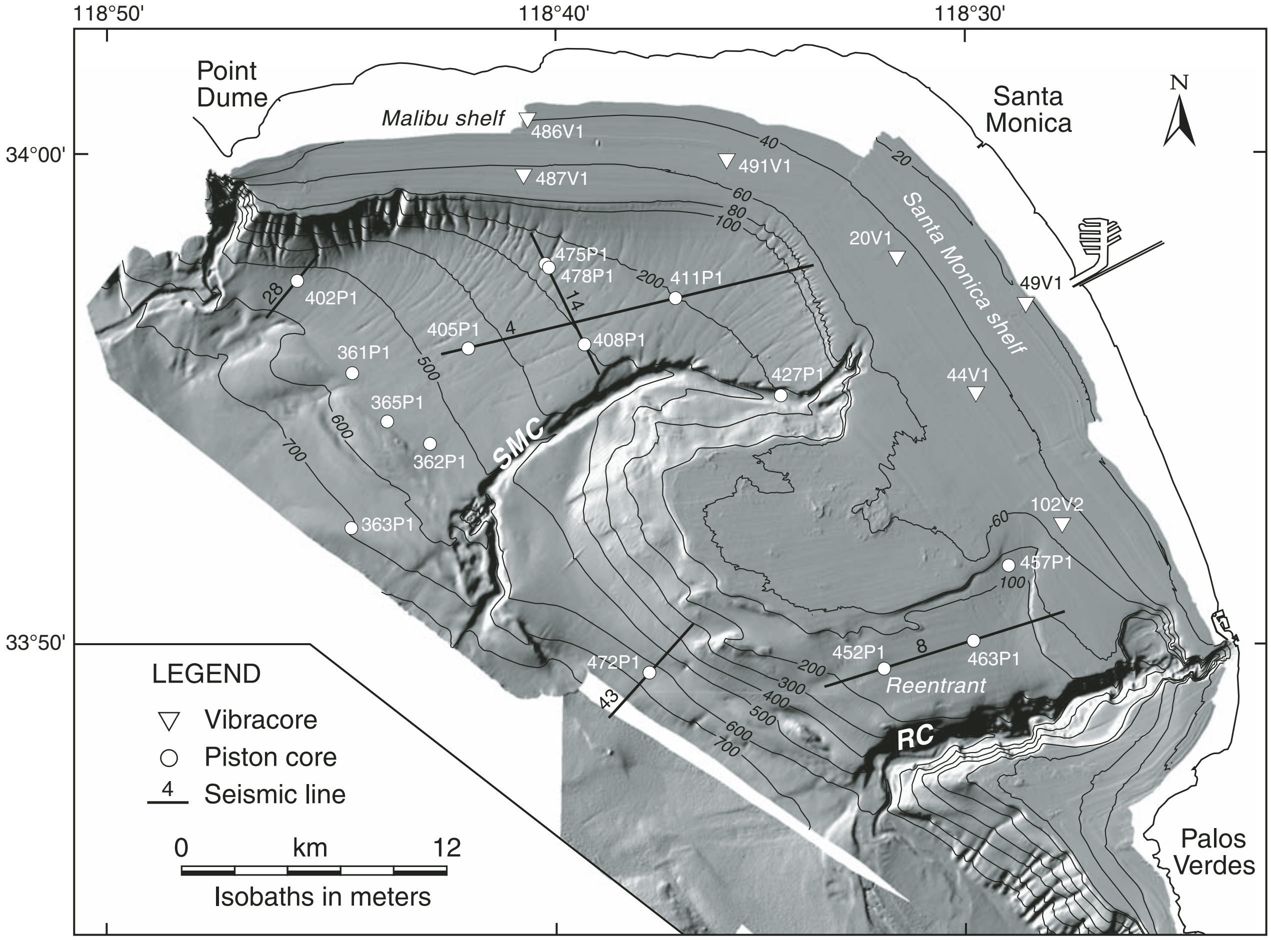

Figure 4. Multibeam bathymetric map of Santa Monica Bay showing the locations of cores and seismic-reflection profiles discussed in the text and shown in figures. Shaded-relief bathymetry and contour lines are from Gardner et al. (1999).

TABLE 1. ACCELERATOR MASS SPECTROMETRY ^{14}C AGE DATES FOR SEDIMENT CORES FROM SANTA MONICA BAY

Core	Depth in core (cm)	Sample type	$\delta^{13}C$ (‰)	^{14}C age † (yr B.P.)	Calibrated age‡ (cal yr B.P.)
452P1	66(a)	Mollusk	2.84	19,600 ± 140	22,320–22,620
452P1	66(b)	Mollusk	1.63	20,000 ± 100	22,670–23,400
452P1	162	Mollusk	0.45	28,800 ± 270	N.A.
452P1	255	Mollusk	0.25	42,500 ± 590	N.A.
457P1	61	Mollusk	1.32	1700 ± 40	920–1160
457P1	212	Mollusk	1.31	6430 ± 45	6500–6790
457P1	348	Mollusk	–2.4	7510 ± 50	7640–7890
457P1	450	Mollusk	0.27	8330 ± 70	8420–8750
478P1	86	Mollusk	1.1	12,570 ± 50	13,690–13,950
478P1	196	Mollusk	–0.09	14,400 ± 75	16,050–16,800
478P1	293	Mollusk	–7.5	15,620 ± 50	18,050–18,580
478P1	357	Mollusk	–0.4	17,290 ± 60	19,570–19,720
478P1	360	Wood	–25.9	16,870 ± 60	N.A.
487V1	32	Mollusk	0.6	11,670 ± 50	12,880–13,080
487V1	147	Mollusk	0.3	13,390 ± 50	14,830–15,340
487V1	245	Mollusk	–1.5	10,570 ± 50	11,210–11,650
491V1	166	Mollusk	–0.73	11,600 ± 65	12,850–13,040
491V1	205	Mollusk	0.04	11,500 ± 60	12,810–12,920

†Conventional radiocarbon age following Stuiver and Polach (1977) with 1σ analytical uncertainty.
‡Reservoir corrected age range (2σ) following Reimer et al. (2004) with ΔR = 220 yr.
N.A.—Not applicable.

were synthesized for this purpose. The first step involved hand-digitizing existing isopach maps. Because acoustic velocities ranging from 1500 to 1700 cm/s were used among the original reports to compute sediment thickness from two-way travel time, it was necessary to normalize all thickness values to a common velocity. This was accomplished by applying a correction factor based on the difference (if any) between previously assumed velocities and a mean measured velocity of 1600 cm/s (Sommerfield and Lee, 2003). Upon merging the older, normalized and new data, overlapping thickness measurements were averaged, and previously extrapolated data points were discarded. Next, the composite thickness data set was interpolated by triangulation and contoured, and the resulting isopach map was georeferenced to NAD83 and registered with National Ocean Service (NOS) bathymetry. Taking into account all possible sources of error, the level of uncertainty in the isopach data is estimated at ±2 m. Isopach maps presented in this paper complement a similar compilation by Slater et al. (2002) by providing continuous coverage of the shelf and uppermost slope in Santa Monica and San Pedro Bays.

RESULTS AND DISCUSSION

Postglacial Sedimentary Cover

The regional isopach map was partitioned into segments consistent with the Santa Barbara, Santa Monica Bay, and San Pedro Bay coastal cells. The uncertain age of the basal seismic-reflection surface used in the original studies to delimit the base of late Quaternary shelf strata does not permit differentiation of late Pleistocene and Holocene units throughout the region. On the other hand, ^{14}C dates correlated with seismic surfaces have allowed us to distinguish lowstand (glacial), transgressive (deglacial–early postglacial), and late transgressive-highstand (late postglacial) units in Santa Monica Bay. Based on insight from Santa Monica Bay, the basal seismic surface mapped in the adjoining coastal cells is likely postglacial in age, created by transgressive ravinement between 13 ka and 10 ka. To simplify matters, *postglacial* will be used henceforth when referring to the age of the mapped sediment prisms.

Santa Barbara Cell

The distribution of postglacial sediments among the three coastal cells is summarized in Table 2. The Santa Barbara cell is defined by Point Conception to the west and Point Mugu to the east (Fig. 1); Hueneme Canyon is the principal sink for sediment moving along-shelf to the southeast, and Mugu Canyon is a secondary sink. This cell contains the largest mass of sediment anywhere on the entire Southern California shelf ($32–42 \times 10^9$ metric tons), the greater proportion of which is present on the eastern end (Fig. 5). Between Santa Barbara and Point Conception, the shelf is mostly a bypass zone with sediment accumulations generally less than 10 m in thickness. Here the shelf is accommodation dominated—the sedimentary cover is discontinuous and rock outcrops are present over large areas of the seafloor. The thin sediment prism can be attributed to several factors including: (1) lack of nearby fluvial sediment sources; (2) negligible sediment transport from sources west of Point Conception; and (3) tectonic uplift, which by steepening the shelf has reduced its trapping capacity (Dahlen et al., 1990).

Between Santa Barbara and Point Mugu, the sediment prism thickens to ≥30 m over a broad area of the shelf directly seaward of the Ventura and Santa Clara Rivers (Fig. 5). Roughly 12 km^3 of sediment is sequestered in this area, a volume equivalent to one third of the total volume of postglacial sediment present on the shelf between Point Conception and Dana Point (30.8 km^3). The large quantity of sediment supplied by the Ventura and Santa Clara Rivers and Calleguas Creek (4.2×10^6 tons/yr; see Warrick and Farnsworth, this volume, Chapter 2.2) distinguishes this supply-dominated segment from others on the margin. By comparison, the fluvial influx to the Santa Monica and San Pedro cells is considerably less at 1.0×10^6 tons/yr and 2.1×10^6 tons/yr, respectively (Warrick and Farnsworth, this volume, Chapter 2.2). During the late Quaternary, sediment supplied from the Ventura and Santa Clara Rivers forced their deltas to prograde over the shelf edge, thereby broadening the shelf and thickening the sediment prism (Dahlen et al., 1990). In addition to the large fluvial influx, late Quaternary sediment accumulation on this shelf segment was apparently enhanced by large-scale subsidence and faulting (Dahlen et al., 1990).

Santa Monica Cell

The Santa Monica coastal cell is bounded by Point Dume and Redondo Canyon to the west and east, respectively (Fig. 1). For convenience, we included the western Palos Verdes shelf when constructing the isopach map for this cell (Fig. 6). Inclusive of the shelf and upper slope (to 500 m water depths), the mass of postglacial sediment sequestered in the Santa Monica

TABLE 2. ESTIMATED POSTGLACIAL SEDIMENT VOLUME AND MASS

Coastal cell	Shelf area (km^2)	Sediment cover (km^2)	Sediment volume (km^3)	Sediment mass (10^9 tons)†
Santa Barbara	1,370	1,200	21.2	32–42
Santa Monica‡	870	660	4.1	6–8
San Pedro‡	1,120	840	5.5	8–11
Totals	3,360	2,700	30.8	46–61

†Computed using a measured dry, bulk-density range of 1500–2000 kg/m^3 (Sommerfield and Lee, 2003).
‡Volume and mass estimates include area between the shelf edge and the 500-m isobath.

cell is ~6–8 × 10^9 metric tons, the smallest amount among the three cells examined in this study (Table 2). Sedimentary cover is thick on the Malibu shelf (up to 25 m) and adjacent to the head of Redondo Canyon, intermediate in thickness off Santa Monica (up to 15 m), and thin to nonexistent over the remaining shelf province (≤5 m). The Malibu shelf depocenter was probably produced by sediment accumulations derived from Malibu Creek and other drainages of the Santa Monica Mountains. Based on the extent of postglacial sediment, the Malibu and Santa Monica shelves fall somewhere between the accommodation- and supply-dominated end members. Late Quaternary sequences underlying the Santa Monica shelf are considerably thicker at 20–60 m (Osborne et al., 1980), so this segment was probably fully supply dominated in the geologic past. Localized depocenters up to 25 m in thickness are present on the western Palos Verdes shelf, and much of this material was delivered by local stream drainage and landslides (e.g., Kayen et al., 2002). The shelf edge throughout the Santa Monica cell is largely devoid of sedimentary cover as is the broad shelf platform between Santa Monica and Redondo Canyons.

Sediment accumulations thicken seaward of the shelf in Santa Monica Bay and form apron deposits on the slope. In particular, a continuous sediment apron reaching 10 m in thickness is present on the slope between Santa Monica Canyon and the Malibu shelf edge, extending across the open boundary of the bay. As elaborated later, this embayed slope is a natural trap for terrigenous sediment, and its sedimentary record provides clues concerning the nature of across-margin sediment movement following the LGM.

San Pedro Cell

The San Pedro cell, bounded by the Palos Verdes peninsula and Dana Point to the west and east, respectively, terminates at Newport Canyon (Fig. 1). The shelf abruptly changes from a broad (20 km) promontory off San Pedro to a narrow (2–3 km) linear segment between Newport Beach and Dana Point. At 8–11 × 10^9 metric tons, the San Pedro cell contains the second largest mass of postglacial sediment in the study area (Table 1), most of which is present on the eastern Palos Verdes and outer San Pedro shelves (Fig. 7). Again, San Pedro shelf appears to fall between the accommodation- and supply-dominated types based on the sediment distribution. In the vicinity of the Palos Verdes fault zone, a southeastward-trending outcrop of exposed bedrock separates major depocenters of the shelf and upper slope. Localized sediment accumulations on the San Pedro shelf include channel fills related to the ancestral Los Angeles and San Gabriel Rivers (McNeilan et al., 1996). These rivers flowed across-shelf within a southeastward-trending paleovalley that terminates at San Gabriel Canyon (Wolf and Gutmacher, 2004). The large volume of postglacial sediment present on the San Pedro shelf was delivered by the former Los Angeles, San Gabriel, and Santa Ana Rivers, and its entrapment was aided by tectonic subsidence of Newport Trough, a depression bounded by the Palos Verdes and Newport-Inglewood fault zones (Bohannon et al., 2004). Between Newport Beach and Dana Point, the relatively narrow shelf limits the amount of sediment sequestered there. In a small area just west of Dana Point, sediment thicknesses reach 15–25 (Fig. 7), material most likely derived from San Jose Creek, nearby coastal drainages, and bluff erosion. Seaward of the shelf

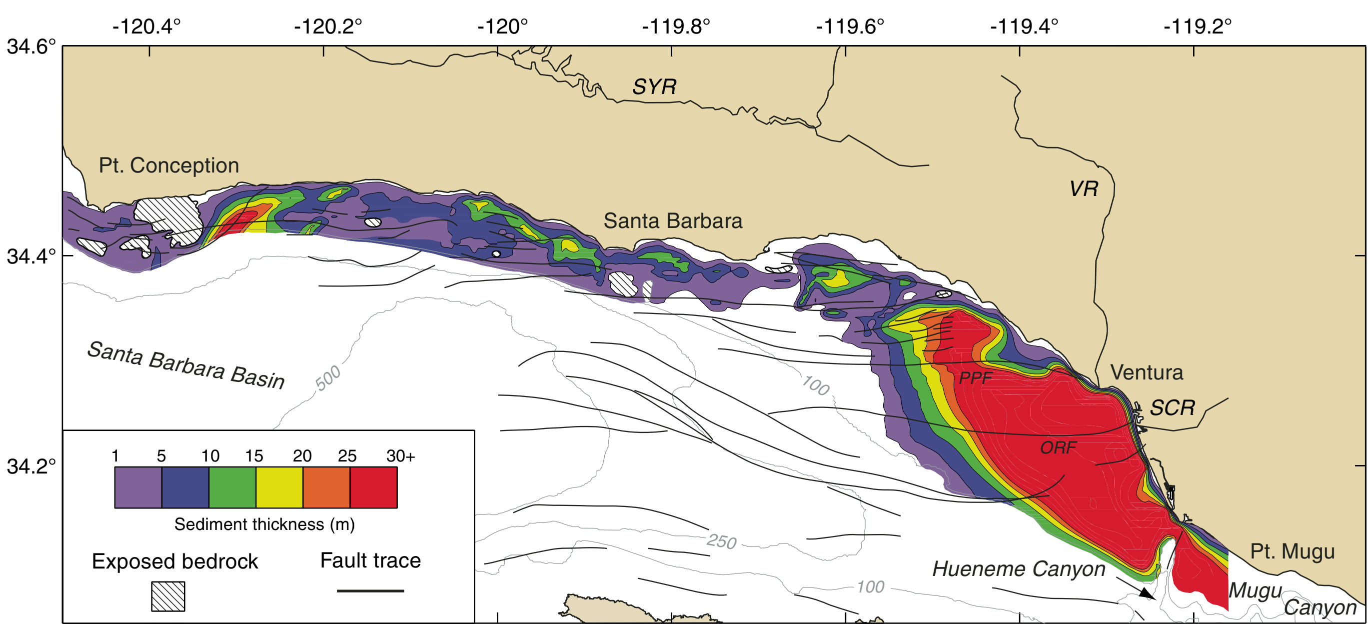

Figure 5. Postglacial sediment isopach map for the Santa Barbara coastal cell constructed from seismic-reflection data sets described in the text. See Table 2 for corresponding sediment volume and mass. Fault traces are from Greene and Kennedy (1987). Abbreviations: ORF—Oak Ridge Fault; PPF—Pitas Point Fault; SCR—Santa Clara River; SYR—Santa Ynez River; VR—Ventura River.

off Dana Point, a 1–5 m thick sediment apron extends over the upper slope, and a similar apron deposit is present between the San Gabriel and Newport submarine canyons .

Fluvial Paleohydrology

Most of what is known about the magnitude and variability of sediment delivery to the Southern California coast is based on records of water discharge and suspended-sediment concentration data for river gauging stations maintained by the U.S. Geological Survey (see Warrick and Farnsworth, this volume, Chapter 2.2). However, measured sediment loads are generally not representative of the postglacial period because of climatic variations in sediment production and continental runoff, not to mention human influences on sediment delivery during historical times (Syvitski and Milliman, 2007). It is well known that the sediment loads of Southern California rivers vary with climatic phenomena such as El Niño (Inman and Jenkins, 1999; Warrick and Milliman, 2003), and that the most extreme floods generate sedimentary event deposits on the continental shelf and within the inner borderland basins (Drake et al., 1972; Soutar and Crill, 1977; Schimmelmann et al., 1990; Behl, 1995; Gorsline, 1996). Yet, here and elsewhere a general understanding of how marine sedimentation responds to climatic variations in continental runoff on the full range of timescales has proven elusive.

Discharge Retrodiction

To constrain the former transport capacity of selected rivers in the study area, we performed a paleodischarge analysis based on the hydraulic geometry of acoustically imaged paleochannels buried just below the shelf seafloor. Back-prediction (retrodiction) of river discharge is possible from paleochannel dimensions

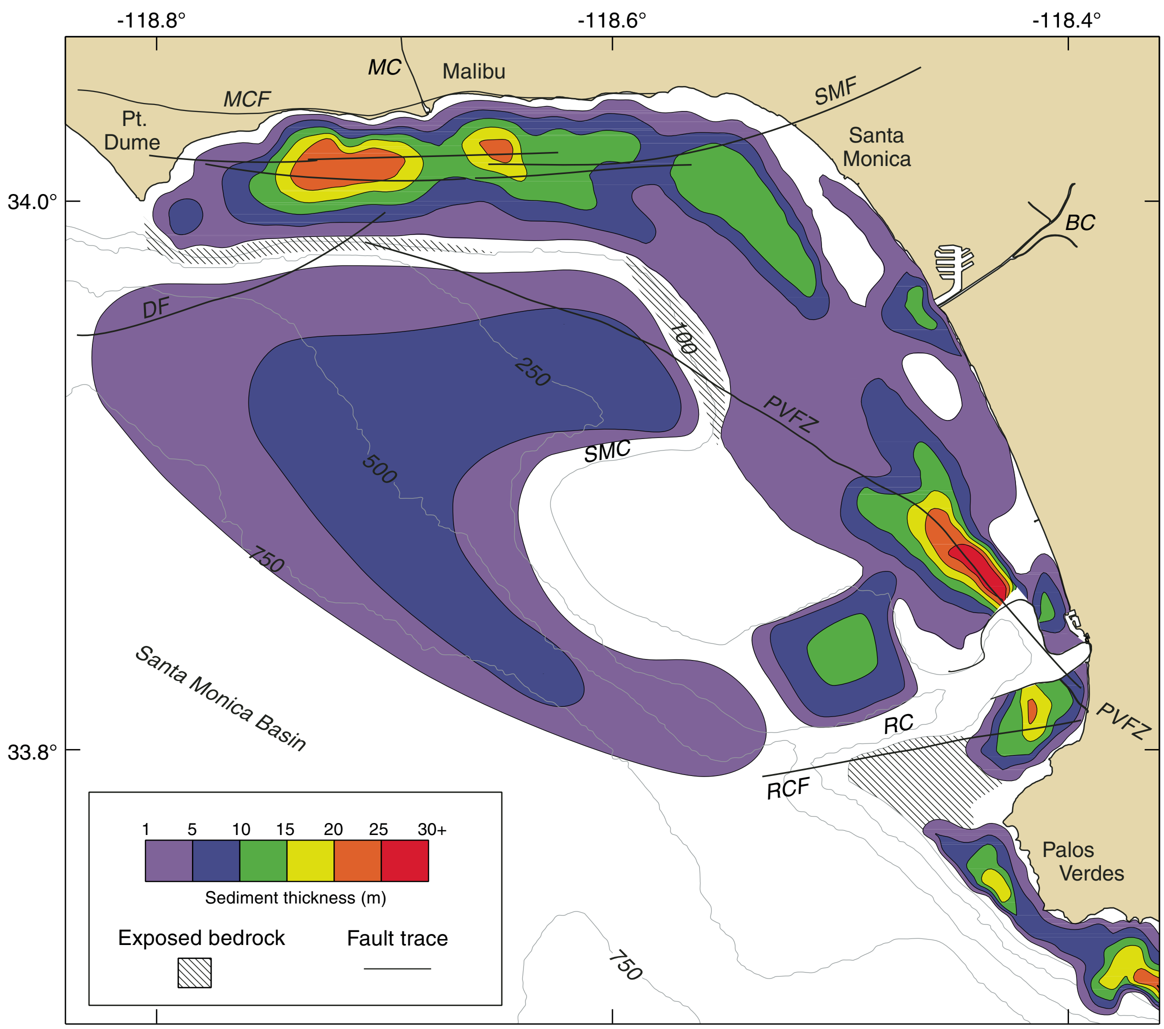

Figure 6. Postglacial sediment isopach map for the Santa Monica coastal cell. See Table 2 for corresponding sediment volume and mass. Fault traces are from Greene and Kennedy (1987). Abbreviations: BC—Ballona Creek; DF—Dume Fault; MC—Malibu Creek; MCF—Malibu Coast Fault; PVFZ—Palos Verdes Fault Zone; RC—Redondo Canyon; RCF—Redondo Canyon Fault; SMC—Santa Monica cell; SMF—Santa Monica Fault.

and continuity relations, or empirical equations developed for modern rivers (Dury, 1985; Rotnicki, 1991). Retrodicted discharge is computed from continuity:

$$Q_r = w\, d\, V_r \,, \tag{1}$$

where Q_r is the bankfull discharge at flood stage, w and d are the respective width and depth of the paleochannel, and V_r is the retrodicted cross-sectional mean velocity. Bankfull discharge of mid-latitude rivers has a recurrence interval of one to two years (Williams, 1978), thus retrodicted flows are generally assumed to be representative of *peakflow* conditions. Paleovelocity is retrodicted independently from Manning's equation:

$$V_r = \frac{R^{0.67} S^{0.5}}{n} \,, \tag{2}$$

where R is channel hydraulic radius, computed as the quotient of channel cross-sectional area (A) and wetted perimeter (P), S is hydraulic gradient, and n is Manning's roughness coefficient, a measure of flow resistance. For alluvial channels, the value of n varies from 0.011 to 0.020 for sandy plain beds to 0.020–0.035 for sand beds with large bedforms (Shen and Julien, 1993). Knowing the grain size of paleochannel fill, Manning's roughness can be computed from Strickler's equation:

$$n = \frac{\left(d_{50}\right)^{0.17}}{21.0} \,, \tag{3}$$

where d_{50} is the median grain size in meters. The Froude Number ($F = V/\sqrt{gd}$) imposes an upper bound on the retrodicted paleovelocity—F is typically less than unity for large alluvial rivers (Rotnicki, 1991). In practice, parameters w, d, and R are measured from interpreted seismic-reflection profiles, whereas S is determined from the channel thalweg gradient between adjacent channel-crossing seismic lines. Although there are more sophisticated methods of retrodiction incorporating channel sinuosity (e.g., Rotnicki, 1991), the preceding equations are appropriate for discontinuous paleochannel segments on the Southern California margin.

Fundamental to discharge retrodiction is the assumption that the measured geometry of a paleochannel is representative for the ancestral river just prior to abandonment and/or transgressive backfilling stage. Here it is important to point out that the width of fluvially incised channels increases during transgression on account of tide and wave ravinement as the system transitions from a nontidal river to a fully tidal estuary. Whereas the cross-sectional area of fluvial channels is controlled by bankfull freshwater discharge, spring tide discharge is the channel-shaping flow

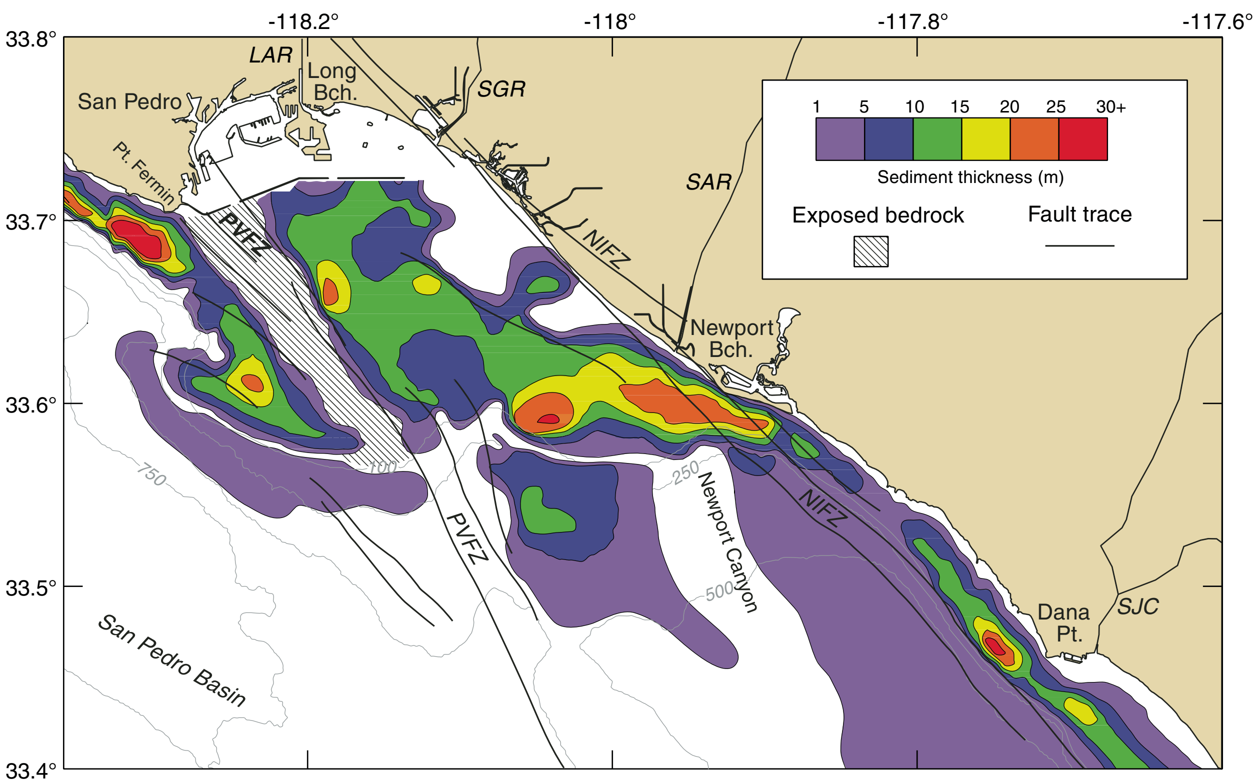

Figure 7. Postglacial sediment isopach map for the San Pedro coastal cell. See Table 2 for corresponding sediment volume and mass. Fault traces are from Greene and Kennedy (1987). Abbreviations: LAR—Los Angeles River; PVFZ—Palos Verdes Fault Zone; NIFZ—Newport-Inglewood Fault Zone; SAR—Santa Ana River; SGR—San Gabriel River; SJC—San Jose Creek.

in tidal rivers and estuaries. Hence, the origin of the erosion surface used to define the channel cross section must be established to place the retrodicted discharge in the proper hydraulic context. Channel width-depth ratio provides a criterion for distinguishing between fluvial and tidal channels in stratigraphic sections: ratios of 10–1000 are characteristic of tidal channels (Lanzoni and Seminara, 2002); and nonbraided fluvial channels have ratios generally less than 40 (Rosgen, 1994). The transgressive stratigraphy of channel fills can provide further constraints on paleohydraulic conditions when the sequence boundary and transgressive erosion surfaces are identified (Nordfjord et al., 2005).

We identified channel segments of the ancestral Santa Clara River, Ballona Creek, Los Angeles River, and San Gabriel River suitable for discharge retrodiction (Fig. 8). Width-to-depth ratios of the selected paleochannels (25–33) are consistent with modern fluvial channels, thus our estimated peak flows are presumed to represent nontidal freshwater discharge to the former coast. For the Santa Clara River, a buried paleochannel mapped by Greene et al. (1978) and Dahlen et al. (1990) provides a representative cross section. Although the absolute age of this channel is unknown, its relative stratigraphy places it within the deglacial interval of the latest Pleistocene (Dahlen et al., 1990). In Santa Monica Bay, shelf paleochannels of Malibu and Ballona Creeks were either destroyed by transgressive ravinement or these drainages existed as unincised alluvial bypass systems at the LGM. However, the dimensions of an onshore paleochannel of Ballona Creek are available for discharge retrodiction, and its late Pleistocene age is biostratigraphically constrained (Poland et al., 1959). In San Pedro Bay, paleochannels of the ancestral Los Angeles and San Gabriel Rivers have been seismically mapped in the shelf subbottom (Greene et al., 1975; Clarke et al., 1983; McNeilan et al., 1996; Wolf and Gutmacher, 2004); we used seismic sections published in McNeilan et al. (1996) and Greene et al. (1975) to retrodict peak paleodischarges for these rivers. The Los Angeles

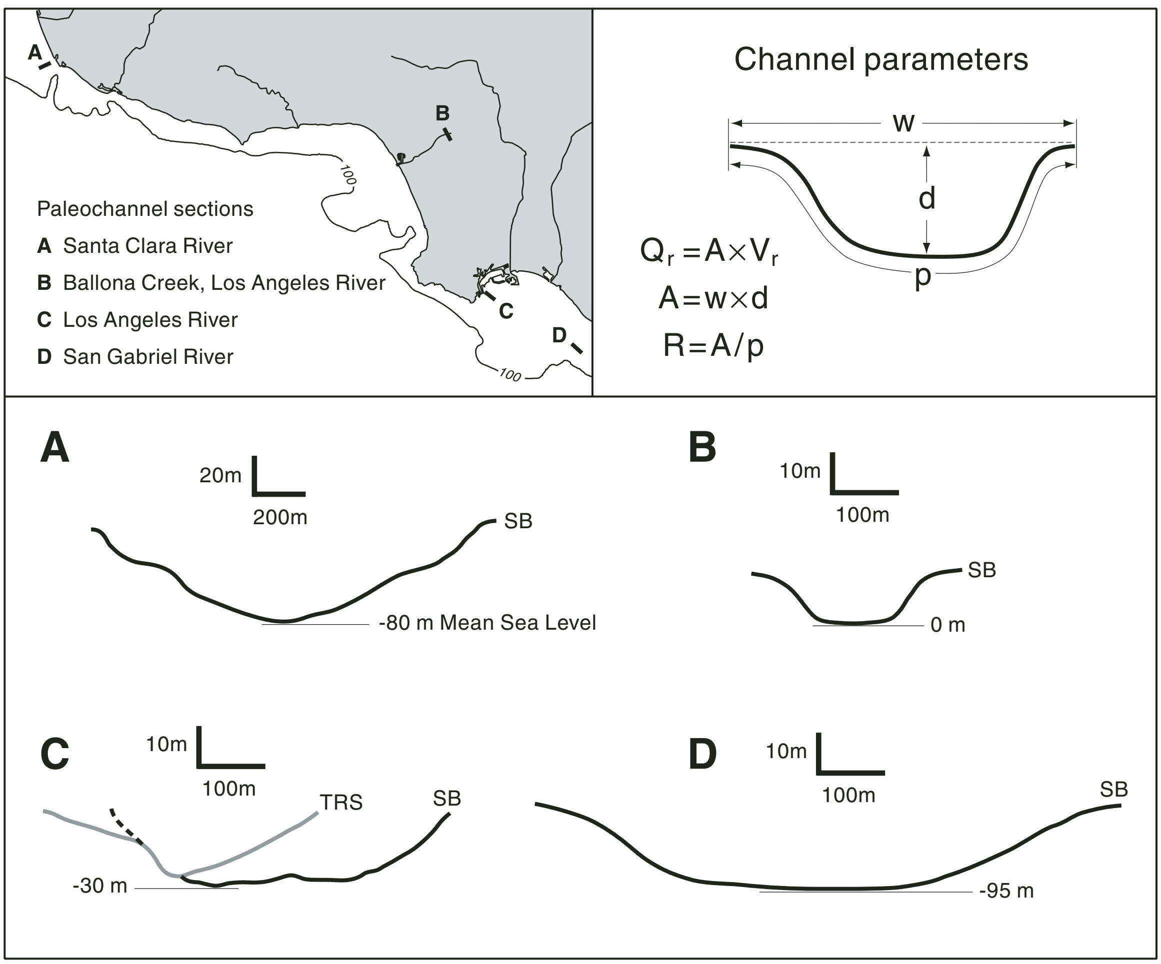

Figure 8. Location and geometry of paleochannel segments used to retrodict peak paleodischarge and sediment load for selected rivers. Channel parameters were referenced to tracings of the sequence boundary (SB) reflector in high-resolution, seismic-reflection profiles. This boundary was considered to approximate the floor of the paleoriver channel, formed by fluvial incision. Care was taken to distinguish the SB from tidal ravinement surfaces (TRS), which evoke erosion by tidal currents during transgression.

and San Gabriel River paleochannels incise coastal strata ranging from 18 ka to 10 ka in age (McNeilan et al., 1996), thus their retrodicted discharges are not necessarily synoptic with paleodischarges estimated for the Santa Clara River and Ballona Creek.

To check the accuracy of continuity-based retrodictions (Equation 1), paleodischarge was also estimated using an empirical equation developed for modern rivers (Williams, 1978):

$$Q_e = 4.0A^{1.21}S^{0.28}, \quad (4)$$

where Q_e is the computed discharge based on measurements of S and A. This equation is based on a regression of measured bankfull discharge, ranging from 0.5 to 28,320 m^3/s, against S and A for 233 mid-latitude rivers. The standard error of the equation is 41% (Williams, 1978). We selected Equation 4 over more elaborate area-slope equations because it requires only two independent variables. Regardless of technique, it is important to emphasize that retrodictions based on channel geometry are not particularly accurate, and individual estimates have been shown to be in error by as much as ±40% (Dury, 1985). On the other hand, the channel geometry method of discharge estimation has proven superior to traditional discharge-watershed area relations (Wharton et al., 1989), and for the present study is satisfactory for arriving at order-of-magnitude estimates of paleoflow.

Measured and retrodicted paleochannel properties are listed in Table 3. As expected, the highest and lowest paleodischarges are indicated for the ancestral Santa Clara River (383–511 × 10^3 m^3/s) and Ballona Creek (8.3–19 × 10^3 m^3/s), respectively. The retrodicted peakflow for Los Angeles River is smaller than that for the San Gabriel River, despite the larger watershed of the former. The Los Angeles River is believed to have periodically flowed to Santa Monica Bay (Poland et al., 1959), so its retrodicted discharge, based on one paleochannel within a larger network, may be an underestimate. Because the retrodicted flows are not synoptic, it is also possible that modern to ancient differences in the relative size of these rivers simply reflect temporal variations in continental runoff and downstream channel geometry. Interestingly, retrodicted peakflow for each paleoriver is one or more orders of magnitude larger than the measured peakflow of its modern counterpart. For example, the paleodischarge of ancestral Santa Clara River (Table 3) is roughly 80–100 times larger than the peakflow of 4500 m^3/s measured during the 1969 flood (U.S. Geological Survey, 2007). Corresponding Froude numbers (0.33–0.43) suggest that the retrodicted discharges are not unreasonable for alluvial rivers, and peakflows computed using Equation 4 are comparable to continuity-based estimates (see Table 3).

Accurate prediction of suspended-sediment discharge (or load in units mass/time) is considerably more challenging than water discharge given that more variables are involved. In general, suspended-sediment load increases exponentially with increasing water discharge as a function of drainage basin size, geology, climate, and other factors (Syvitski et al., 2003). The most common approach of predicting sediment load at a river gauging station involves power functions relating measured water discharge, suspended-sediment concentration, and sediment load (Syvitski et al., 2000). Adapted for retrodicted data, the power function has the following form:

$$Q_{sr} = aQ_r^{\,b}, \quad (5)$$

where Q_{sr} is the retrodicted instantaneous sediment load, Q_r is retrodicted instantaneous water discharge from Equation 1, and a and b are derived parameters.

To estimate former sediment loads of Ballona Creek, Los Angeles River, and San Gabriel River, all of which lack sediment rating parameters, we used suspended-sediment data for the Santa Clara River as a proxy (U.S. Geological Survey, 2007). For the period 1967–1981, daily mean water discharge (m^3/s) was regressed against suspended-sediment load (metric tons/s) and fit with a power function to derive the rating parameters ($a = 0.0033$ and $b = 1.58$). These parameters and values of Q_r (Table 3) were then substituted into Equation 5 to estimate past sediment loads. The underlying assumptions are that (1) rating parameters for the modern Santa Clara River are representative for its ancient counterpart, and that (2) the parameters are equally representative for the other rivers considered in this study. These assumptions are uncertain because the watersheds are likely to have unique sediment-production characteristics, and also because sediment production, storage, and delivery to the coast must have varied temporally with climatic changes in precipitation and land-surface conditions. As another caveat, bedload is not considered in these estimates—suspended-sediment paleodischarges reported herein are minimum estimates of the total load.

Retrodicted peak sediment loads range from a high of 2000–3200 metric tons/s for the ancestral Santa Clara River to a low of

TABLE 3. PALEOCHANNEL PROPERTIES AND DISCHARGE RETRODICTIONS FOR SELECTED COASTAL RIVERS

Channel	w (m)	d (m)	A (×10^3 m^2)	V_r† (m/s)	Q_r (×10^3 m^3/s)	Q_e‡ (×10^3 m^3/s)	Q_{sr} (tons/s)
Santa Clara River	1400–1500	35–40	49–60	7.8–8.5	383–511	225–288	2000–3200
Ballona Creek	250–300	10–15	2.5–4.5	3.3–4.3	8.3–19	6.2–13	5–18
Los Angeles River	500–550	15–18	7.5–9.9	4.4–5.0	33–49	23–33	42–79
San Gabriel River	850–900	20–25	17–23	5.4–6.2	91–140	63–88	212–413

†Computed using Equations 2 and 3 with the following constants: $d_{50} = 1 \times 10^{-3}$ m, $n = 0.03$, and $S = 5 \times 10^{-4}$. See text for description of variables and constants.

‡Computed from Equation 4 using measured values of S and A.

5–18 metric tons/s for the former Ballona Creek (Table 3). By comparison, the maximum measured load of the Santa Clara during historical floods is 75–214 tons/s (Farnsworth and Milliman, 2003), considerably smaller than the retrodicted range. In terms of suspended-sediment load, the ancestral Los Angeles and San Gabriel Rivers would have been comparable to the modern Santa Clara at flood stage, whereas the former Ballona Creek would have been analogous to larger coastal rivers of central California.

The substantial difference between retrodicted and contemporary river discharges and sediment loads is mostly a consequence of the relatively large cross-sectional area of the paleochannels, which would have been in equilibrium with continental runoff during the deglacial period. On middle- to northern-latitude coasts worldwide, fluvial channels enlarged by meltwater flow were equilibrated to discharges up to several orders of magnitude greater than Holocene peakflows (e.g., Gallagher, 2002). Although the Los Angeles drainage basin was not glaciated, a wealth of evidence suggests that deglacial climates in the region were considerably cooler and wetter than during postglacial and historical times, and thus conducive for generating large freshwater discharges. The paleohydrologic history of the region is known from marine and lake sedimentary records from Santa Barbara Basin (Heusser, 1978), Owens Lake (Mensing, 2001), and the Mojave River drainage basin (Enzel et al., 2003). The period from 18 to 11 ka was cool and very wet in Southern California, with annual precipitation rates two to three times higher than the relatively warm and dry Holocene (Mensing, 2001). The hydrologic reconstruction for pluvial Lake Mojave (Wells et al., 2003) is particularly relevant to the Southern California coast; the San Bernardino Mountains were not glaciated at the LGM, and lake water volumes and sedimentation rates fluctuated in accord with periods of intense rainfall (pluvials) associated with deglacial climates (Wells et al., 2003). The Lake Mojave record indicates that sediment accumulation was continual from 22 ka to ca. 9 ka, after which the lake desiccated. Maximal rates of sediment accumulation occurred from 21 to 18 ka, and again from 15 to 14 ka, owing to periods of particularly intense rainfall runoff. By extension, river flow and sediment delivery to the Southern California coast would have increased during the pluvial phases.

Although speculative, the paleohydrologic analysis helps explain differences in the volume of postglacial sedimentary cover along the Southern California shelf. The parallel between sediment mass, retrodicted discharge, and sediment load (see Tables 1 and 3) suggests that the relative amount of sediment sequestered within the coastal cells is a function of supply variables, in particular, fluvial sediment load. Whereas the accommodation variables appear to be subordinate to sediment supply in controlling the overall mass of postglacial sediments on the shelf, the location and geometry of some sediment depocenters seem to be determined by accommodation space imparted by shelf tectonism and antecedent topography. A more rigorous reconstruction of continental runoff following the LGM is needed to better constrain the nature of sediment delivery to the coast. Additionally, further research is needed to clarify the relative influences of local sediment supply and tectonic accommodation on patterns and rates of sediment sequestration on the margin.

Deglacial to Postglacial Sedimentary Record

Previously we have correlated sedimentary records of Southern California shelf, slope, and inner basins in an effort to reconstruct the magnitude and variability of across-margin sediment movement following the LGM (Sommerfield and Lee, 2004; Normark and McGann, 2004; Normark et al., 2006; also see Normark et al., this volume, Chapter 2.6). In this section we focus on the post–LGM sedimentary record of Santa Monica Bay, which presents a good case study area for examining relationships between sea level, shelf morphology, and sediment accumulation. Below, sedimentary sequences of shelf, apron, and marginal slope provinces of the bay are discussed separately.

Shelf Province

A large number of ^{14}C dates are now available to provide chronological control for shelf strata in Santa Monica Bay (Sommerfield and Lee, 2003; Sommerfield and Lee, 2004; also see Table 2). On the basis of age and lithology, the shelf sediment column can be subdivided into (1) a late deglacial unit, and (2) a postglacial unit. The most diverse record is provided by core 49V1 (Fig. 9), which penetrated the modern sediment prism and recovered paleochannel fill deposits of Ballona Creek—this paleochannel does not extent seaward of the innermost shelf. Cores 20V1 and 102V1 contain a wave ravinement surface formed by shoreface erosion during transgression. Below the wave ravinement surface, the deglacial interval consists of sands deposited in a transitional, moderate energy environment landward of the shoreface; a nonmarine depositional environment is evidenced by presence of estuarine mollusks and foraminifera (R. Boettcher, 2003, personal commun.). Above the ravinement surface, the deglacial unit is composed of coastal sand and sandy gravel with abundant shell fragments, indicative of a high-energy surf zone. These sediments comprise the top of the transgressive sand sheet, which, because of its acoustic impedance contrast with overlying, finer grained sediments, has previously been interpreted as the base of the "Holocene" succession (Osborne et al., 1980; Slater et al., 2002). On both the Santa Monica and Malibu shelves the lower portion of the postglacial unit is composed of fine-grained sand and sandy silt characteristic of a fully marine, inner-shelf environment, an interpretation supported by presence of neritic species of foraminifera. Off Santa Monica, the sediment column fines upsection from marine silts and sands to clayey silts of the present seafloor. This upward fining sequence is broadly consistent with a progressive increase in wave base depth, i.e., a decrease in near-bed energy level during transgression (Nummedal and Swift, 1988).

Cores collected on the Malibu shelf did not recover strata correlative with the late deglacial unit off Santa Monica (Fig. 9). Inverted ^{14}C age dates (older ages above younger ones) are present in cores 487V1 and 491V1 from Malibu shelf, suggesting that the material dated was reworked from older strata, and that the sediment column is considerably younger than implied by the age dates. Assuming the age-depth relationship for core 486V1 is representative for the other sites, the maximum age of strata recovered at these Malibu shelf sites is ~4000 yr.

Linear sediment-accumulation rates derived from ^{14}C age dates range from 15 to 52 cm/1000 yr (Sommerfield and Lee, 2003). These long-term rates are considerably lower than rates of eustatic sea-level rise during the late Holocene (1–2 mm/yr; Fleming et al., 1998), and also rates determined from tide-gauge records for the coast of Southern California (1–2.2 mm/yr; National Ocean Service, 2007). The relatively low sediment-accumulation rates suggest that accretion of the shelf seafloor is not in equilibrium with depositional base level, which in the shallow-marine environment is generally set by storm wave base. This finding confirms our interpretation that the Holocene shelf of Santa Monica Bay is accommodation dominated, and implies that it has further capacity to sequester sedimentary materials derived from local and distal sources.

The ^{14}C geochronology of Santa Monica shelf cores permits an interpretation of transgressive coastal and marine sedimentation following the LGM. Sediment facies in core 102V2 reveal that the transition from nonmarine (or marginal marine)

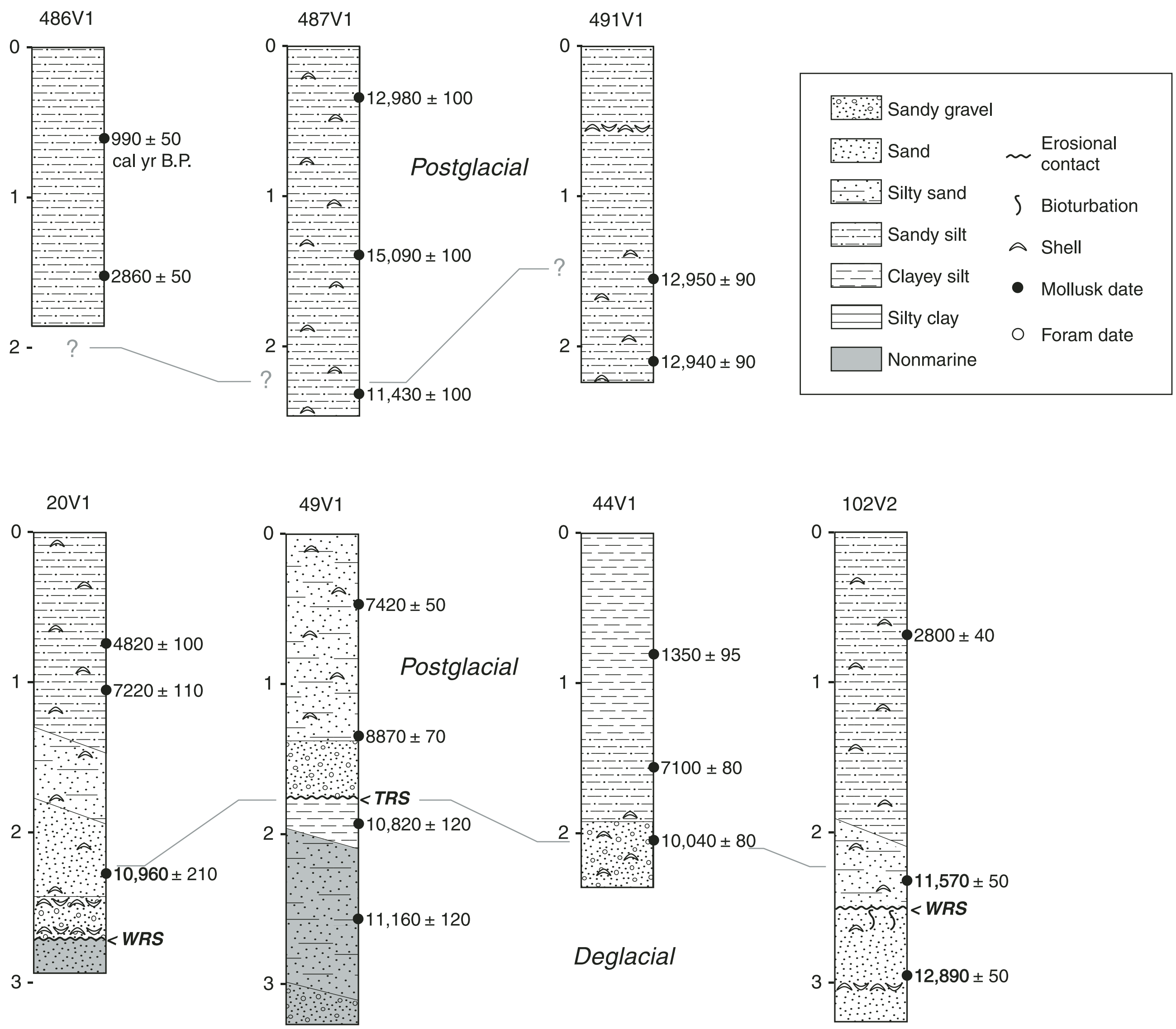

Figure 9. Lithology and ^{14}C age dates (all in cal. yr B.P.) for cores collected within the Santa Monica Bay shelf province. See Figure 4 for sample locations. These cores document transgressive sedimentation from the late deglacial interval through postglacial times. Wave-ravinement surfaces preserved in cores 20V1 and 102V2 provide evidence of paleoshoreface erosion. Abbreviations: TRS—Tide ravinement surface; WRS—wave ravinement surface.

to shallow-marine conditions occurred locally at ca. 13 ka. The former shoreline would have been at ~60 m below present sea level according to the eustatic sea-level curve shown in Figure 3. Based on the elevation of the wave ravinement surfaces in cores 20V1 and 102V1, the shoreface would have retreated to the present 50-m isobath by 11.5 ka. The transition from nonmarine to shallow-marine depositional conditions on the present inner shelf occurred at ca. 11 ka. In core 49V1 this is manifested by a marine flooding surface, a conformable contact between fluvial silty sand and estuarine silt. With continued marine flooding some of the estuarine strata were eroded, and sand and gravel transported landward from the paleoestuary mouth was deposited atop the erosion bed, forming a tidal ravinement surface (Fig. 9). Based on the stratigraphy of core 49V1, shallow-marine conditions prevailed in Santa Monica Bay by 9–8 ka. The transgressive stratigraphy of Santa Monica shelf is broadly consistent with that of the neighboring San Pedro shelf; McNeilan et al. (1996) report that transgressive sedimentation terminated around 8 ka with backfilling of the paleochannels of the Los Angeles and San Gabriel Rivers. In both bays, shelf muds accumulated after 8 ka, forming wedge- and lens-shaped sediment prisms (Figs. 7 and 8). Despite regional tectonism, this sedimentary record is consistent with the archetypical transgressive sequence proposed for passive-margin shelves (Nummedal and Swift, 1988).

Apron Province

The continental slope off Southern California links the coastal cells to deepwater depositional systems via submarine canyons and numerous seafloor gullies. Sediment accumulations on the slope are derived from allochthonous fluvial sediments, in addition to coastal and shelf sediments redistributed seaward by wave ravinement during the postglacial transgression. Not surprisingly, the slope sedimentary record of transgression in Santa Monica Bay is highly variable and reflects local interactions between sea-level inundation and seafloor morphology.

In the northwestern portion of Santa Monica Bay, a broad sediment lens cut by numerous gullies is the most conspicuous feature of the slope apron province (see Figs. 4 and 6). Huntec reflection Line 4 trends along-strike seaward of Santa Monica shelf, capturing the shallow subbottom stratigraphy of this area (Fig. 10). Here the seafloor is underlain by an acoustically stratified sediment lens, which is ~18 m in thickness at the 150 m isobath, thins downslope, and eventually pinches out at the bay mouth in 550–600 m water depths. Based on age dates for cores 411P1 and 405P1 along Line 4, the base of this unit (Reflector R in Fig. 10) is consistent with the sequence boundary between the last lowstand and transgressive deposition. Within this unit a strong, seafloor-parallel reflector (Reflector R1) can be traced from the shelf edge to ~500 m water depth. The lithology of core 411P1 reveals that this reflector is created by the acoustic impedance contrast between bioturbated clayey silt and the underlying sandy silt (15–20 µm mean grain size). The clayey silt was deposited after 11–10 ka during postglacial times, whereas the basal sands were emplaced during an earlier stage of transgression as healing phase deposits (Fig. 10). This interpretation is supported by the sedimentology of the basal sands, which is nearly identical to that of fine sand on the modern inner shelf of Santa Monica Bay. During the earliest transgression this material would have been delivered directly to the upper slope by river outflow, or swept off the shelf through wave resuspension.

A complete glacial-to-postglacial sequence is recorded in core 405P1 (Fig. 10). The sediment column fines upward from silty clay with sand (25% by weight) to uniform, bioturbated silty clay with <10% sand, a transition that ^{14}C dates indicate occurred during the deglacial between 15,560 and 12,090 cal. yr B.P. A similar glacial-to-deglacial decrease in fine sand content has been reported for other sites on the Southern California margin (Behl, 1995; Behl et al., 2000), a change we interpret to reflect reduced suspended-load transport of fine sand from the shelf to slope. Rising seas would have reached the shelf edge by ca. 13 ka, triggering transgressive sedimentation conditions on the shelf under a reduced land-to-ocean hydraulic gradient. During transgression, only the most shore-proximal slope depositional sites would have received suspended sand from river or storm-generated sediment plumes emanating from the shelf.

The morphology and internal bedding of the apron gullies reveal that they are accretionary features created by sediment-laden flows generated upslope on the shelf. As first described by Gardner et al. (2003), individual gullies are generally less than 4 m deep, up to 100–200 m in width, and several kilometers in length. Huntec acoustic reflection profiles reveal that many of these gullies mirror relict gully morphology in the subbottom (see Fig. 11). Recent sediment accumulation has accentuated the topography of some gullies, whereas others have been completely blanketed and smoothened. The gully stacking pattern is suggestive of phase-like activity during the late Quaternary, similar to gully sequences preserved on the Northern California slope (Field et al., 1999) and European margin (Chiocci and Normark, 1992). In Santa Monica Bay, gullies are associated with the deglacial and postglacial depocenter (see isopach map in Fig. 6), which is composed of an acoustically stratified unit whose contact with underlying acoustically transparent strata is correlative with Reflector R (Fig. 11). The geometry and internal stratification of the upper unit suggest that sediment-gravity flows generated on the shelf bypass the relatively steep basin slope, decelerate and deposit some fraction of the suspended load over the apron.

Piston cores obtained along Huntec line 14 provide a well-dated composite record of apron depositional processes during deglacial and postglacial times (Fig. 11). Deposits in the apron province are generally bioturbated and outwardly uniform in appearance, but intervals of some cores contain beds of internally laminated silt, clay, and finely disseminated shell (Fig. 12). These beds are consistent with dilute turbidity current deposits (Mulder and Alexander, 2001), perhaps created by underflows generated by river floods or storm-wave resuspension on the shelf. Importantly, such beds can explain the acoustic stratification of the deglacial to postglacial unit in Huntec reflection profiles. Core 408P1 is composed of olive gray, bioturbated clayey silt deposited after ca. 7.8 ka, based on the basal ^{14}C age date (Fig. 11). Although this core did not penetrate the acoustically stratified unit at its thickest point, the base of the unit was indeed reached by core 478P1 upslope on the flank of a 200-m-wide gully. Here the sediment column fines upsection from clayey silt to silty clay, all of which was emplaced between 19.7 and 13.7 cal. yr B.P (Fig. 11). The basal age date confirms that the acoustically stratified unit began to accumulate around the time of transition from lowstand to transgressive conditions, whereas the old core-top age indicates that the gully flank has been nondepositional or erosional throughout postglacial times. Modern sediment bypass is confirmed by a lack of measurable ^{137}Cs activity in core-top sediment (C. Alexander, 2002, personal commun.).

In an attempt to resolve differential sediment-accumulation rate across a gully section, core 475P1 was collected in the thalweg adjacent to and just upslope of core 478P1. Here a complete postglacial section is preserved, and based on presence of ^{137}Cs activity in core-top sediments, the modern seafloor appears to be accretionary. ^{14}C age dates suggest that sediment-accumulation rates at the gully flank decreased from 0.4 to 0.5 mm/yr at the LGM to 0.1 mm/yr, averaged over the deglacial period. Similarly, sediment accumulation in the gully thalweg decreased from a rate of 2 mm/yr during the deglacial to 0.2–0.4 mm/yr during

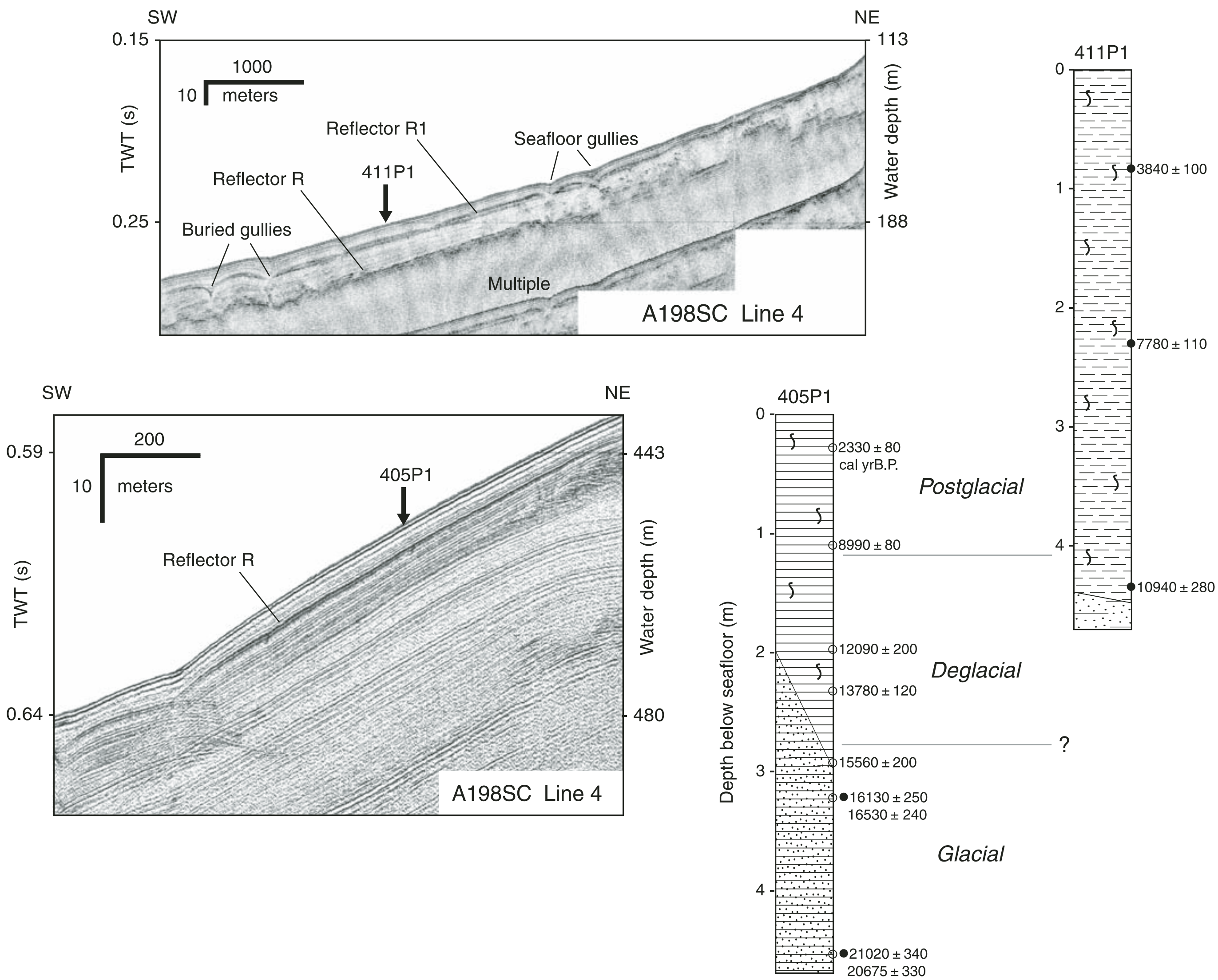

Figure 10. Huntec seismic Line 4 (partial) and core lithology and geochronology for sites in the Santa Monica Bay apron province. See Figure 4 for sample locations and Figure 9 for lithologic symbols. At site 405P1, the transition from late glacial lowstand sedimentation to deglacial transgressive conditions is evinced by an up-core decrease in the content of fine sand. This change corresponds to an upsectional decrease in the degree of seismic stratification above Reflector R, interpreted as the base of the transgressive sequence. At site 411P1, the transgressive sequence above Reflector R is relatively thick and contains an internal reflector (R1) correlative with fine sand emplaced around 11 ka. This sand layer is consistent with transgressive healing-phase deposition discussed in the text. TWT—Two-way travel time.

postglacial times. Because the thalweg core did not penetrate glacial strata, it is not possible to compare across-gully accumulation rates when it was actively conveying sediment. Nonetheless, the composite record provided by cores 475P1 and 478P1 suggests that differential sediment-accumulation rate across the gully, rather than erosional scour of the thalweg, can explain the channel-like morphology of this and other gullies on the slope. These gullies are evidently accretionary features, unlike incised gullies or canyons. In sum, relatively rapid sediment accumulation occurred over the slope apron during late glacial and deglacial times, followed by patchy hemipelagic blanketing of gully topography during the ensuing postglacial interval.

Marginal Slope Province

The marginal slope of Santa Monica Bay forms a broad reentrant to Redondo Canyon, the head which is believed to

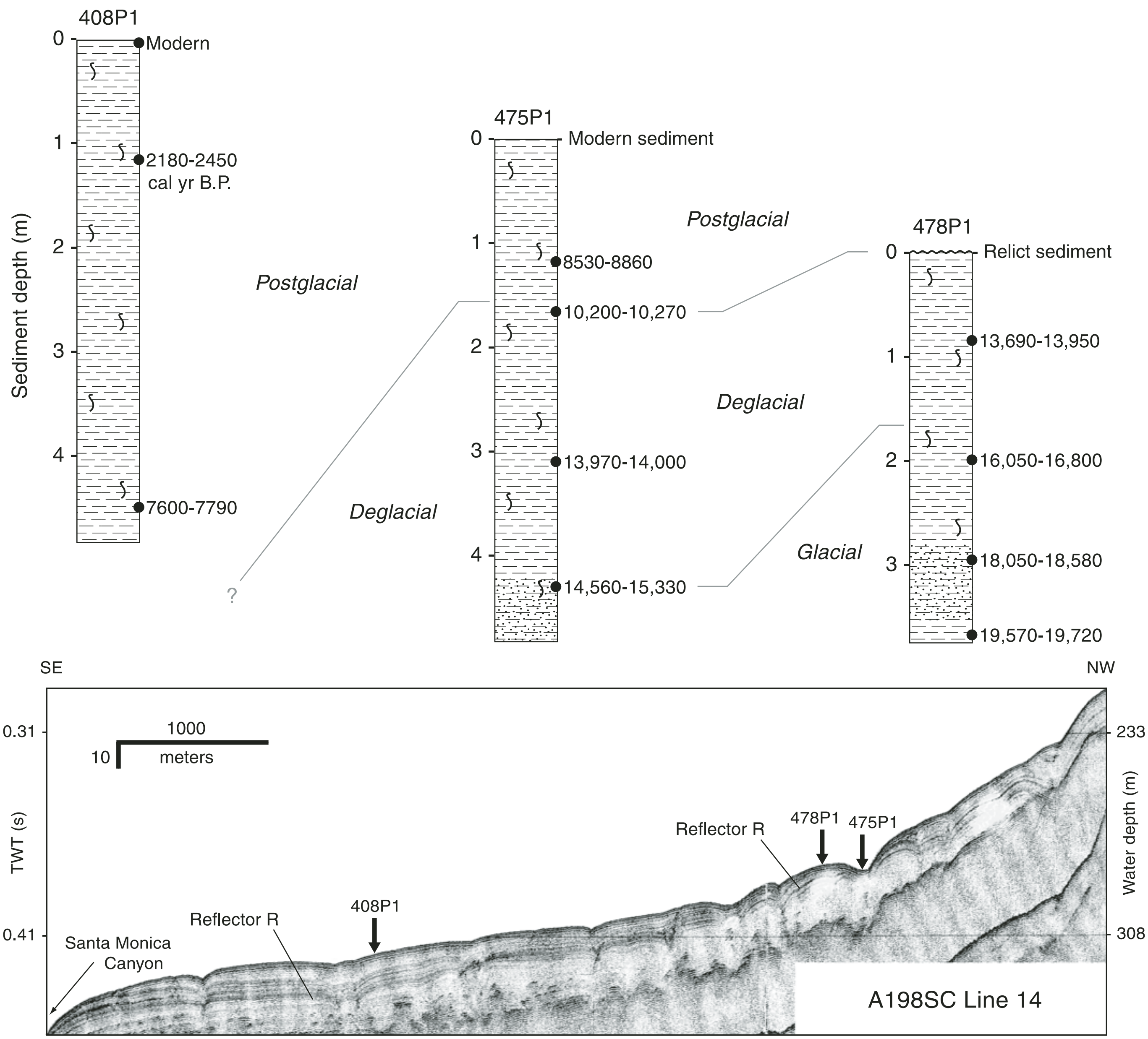

Figure 11. Huntec seismic Line 14 (partial) and core lithology and geochronology for sites in the Santa Monica Bay apron province. See Figure 4 for sample locations and Figure 9 for lithologic symbols. Cores 408P1 and 475P1 record sediment accumulation during the deglacial and postglacial phases. Core 478P1, which reached Reflector R, archives the late glacial and deglacial. The flank of the broad gully (Site 478P1) has been a sediment bypass zone since the late glacial, whereas the thalweg (Site 475P1) has been accretionary throughout postglacial times. Note that rates of sediment accumulation during the postglacial were significantly lower than those during the glacial and deglacial intervals. TWT—Two-way travel time.

have been incised by a paleoriver valley during a late Quaternary lowstand (Osborne et al., 1980; Gardner et al., 2003). Here the pattern of sediment accumulation is clearly controlled by interactions between bottom flows and tectonically produced topography. A seismic-reflection profile crossing the shelf-to-slope transition reveals inclined late Quaternary coastal strata at the shelf edge, a 15- to 20-m-thick lens of moderately stratified and gas-charged sediments within the reentrant, and a highly stratified sediment drape atop deformed strata at the reentrant mouth (Fig. 13). Cores of the lens-shaped sediment package (sites 463P1 and 457P1) consist of olive gray, bioturbated clay silts, and the material recovered is less than 8750 cal. yr B.P. in age. As observed in the apron province, linear sediment-accumulation rates on the marginal slope decreased by about a factor of two after 6–7 ka, from 1 to 1.2 to 0.3–0.7 mm/yr. Given these rates we estimate that the base of the sediment lens formed ca. 19–20 ka. The lens thins seaward and becomes condensed at the reentrant mouth before thickening again in deeper waters. A core of the condensed section (452P1) yielded ^{14}C age dates that increase from 22,320 to 43,100 cal. yr B.P. downcore (0.06 mm/yr mean accumulation rate), predating the LGM (Fig. 13). Hence, while sediment accumulation filled low topography within the reentrant, the reentrant mouth was nondepositional or erosional. This accumulation pattern may result from internal-wave resuspension. For example, elsewhere in the bay shoaling internal waves are known to rework the seafloor at the shelf edge (Noble and Xu, 2003).

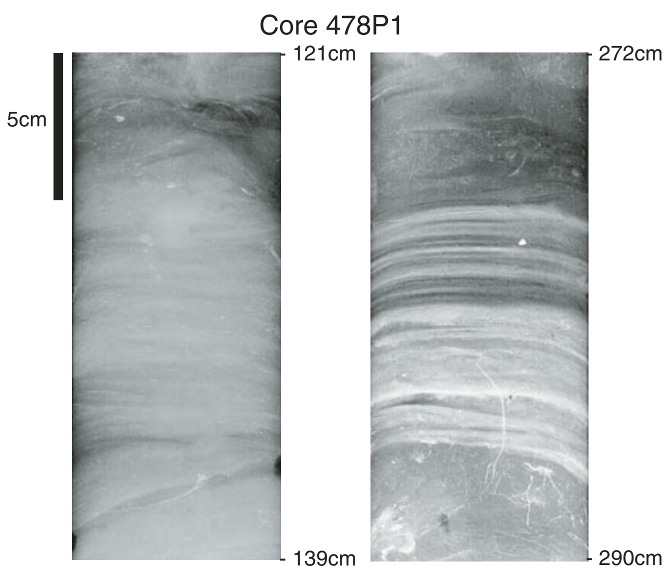

Figure 12. X-radiograph negatives for two intervals of core 478P1 showing sedimentary fabrics created by different modes of deposition within the slope apron province. The lighter grayscale shades correspond to the denser sediment grains or beds. (Left) Bioturbated clayey silt with very faint physical stratification produced by hemipelagic deposition. (Right) Interbedded and laminated silty clay with very fine sand deposited under one or more dilute sediment-gravity flows. The hair-like features in the laminated interval are pyritized microburrows.

At the mouth of Santa Monica Bay, the outer marginal slope is characterized by a seaward-thickening sediment drape with some acoustic stratification (Fig. 14). Much of the open continental slope off Southern California is characterized by this form of sediment accumulation, i.e., patchy sediment blanketing with little evidence of mass movement (Nardin, 1983). These drapes form by sediment accumulation under the Southern California Counter Current, which from the southeast to northwest sweeps the slope and innermost basins, dispersing lithogenic and biogenic material derived from various sources (Huh et al., 1990; Hein et al., 2003). The lithology of core 472P1 is consistent with hemipelagic sediment: olive gray, bioturbated silty clay with no sand or shell debris (Fig. 14). Similarly, core 402P1 at the seaward end of the apron province is composed of highly uniform, hemipelagic silty clay. The ^{14}C age dates indicate that the cored sediment column is <12 k.y. in age and that rates of accumulation (0.4–0.6 mm/yr) were largely invariant during postglacial times. Apparently, these depositional sites were not impacted by changes in bay sedimentary processes brought about by postglacial sea-level rise and transgression, perhaps because they are somewhat removed from the mainland shelf edge. However, strong seismic reflectors are present in the subbottom below the cored depths (see Fig. 14), thus lowstand or early deglacial deposition may have involved relatively coarse-grained sediments derived from the shelf.

Shelf-to-Slope Sediment Delivery

The mosaic of findings from this and related studies provide an opportunity to evaluate longstanding concepts of lowstand-to-highstand marine sedimentation that form the basis of siliciclastic sequence stratigraphic models in wide use today. For a tectonically passive margin, the general model of a eustatically forced sedimentary cycle holds that sediment delivery to continental slope and deeper environments is maximal during times of falling sea level, because excavation of coastal valleys and submarine canyons adds sediment to the allochthonous fluvial supply. With depletion of erosional sources, rates of sediment delivery decrease at late lowstand, and decrease further with sea-level rise and transgression, backfilling estuaries, fluvial channels, and coastal valleys. Not until highstand conditions are established, perhaps with seaward progradation of river deltas and coastal sediment prisms, do sediment delivery rates increase and approach lowstand rates. Despite active tectonism on the California margin, there is ample evidence of eustatically controlled marine sedimentation (e.g., Gorsline et al., 1968; Nardin, 1983; Thorton, 1984; Normark et al., 1998; Sommerfield and Lee, 2004; Normark and McGann, 2004; Normark et al., this volume, Chapter 2.6), thus the basic tenet of the sequence stratigraphic model is appropriate. Then again, local basin factors including tectonic accommodation and climatic changes in sediment delivery appear to have moderated patterns and rates of postglacial sediment accumulation on the margin, as described below.

Linear sediment-accumulation rates at ODP Sites 1017 and 893, and slope apron sites within Santa Monica Bay (see Fig. 1

for locations) were maximal during the deglacial period (10–15 ka), not during the late glacial lowstand as specified by the general model. Rates then decreased during 10–5 ka and further during 5–0 ka, a trend recorded by slope apron strata in Santa Monica Bay (Fig. 15). In contrast, sediment-accumulation rates at ODP Site 1015 in Santa Monica Basin remained high (4 mm/yr) from 22 to 8 ka (Normark and McGann, 2004; Normark et al., 2006). This difference reflects the fact that Hueneme Canyon is the primary source of sediment to the basin, not sources within the more proximal Santa Monica Bay. Most of the sediment column at Site 1015 is composed of turbidite sands, whereas hemipelagic muds comprise the late glacial, deglacial, and postglacial intervals at Sites 1017 and 893. Because the turbidite beds comprise a disproportionate fraction of the sediment column, they effectively increase Site 1015 sediment-accumulation rates relative to those at Sites 1017 and 893. When turbidite intervals are excluded from the Site 1015 record, the hemipelagic sediment-accumulation rates are comparable to those elsewhere in the inner basins, though a phase of maximum LGM–deglacial accumulation rate is still apparent (see Normark et al., this volume, Chapter 2.6). These findings suggest that the general sequence stratigraphic model is not well suited to deepwater depositional systems characterized by distributed sources of terrigenous-hemipelagic sediment.

The period of maximal sediment accumulation during 15–10 ka can be interpreted in the context of local basin factors. The deglacial period was characterized by a wide range of hydrologic and oceanic changes, not the least of which was the onset of coastal plain flooding with sea-level rise above the shelf edge.

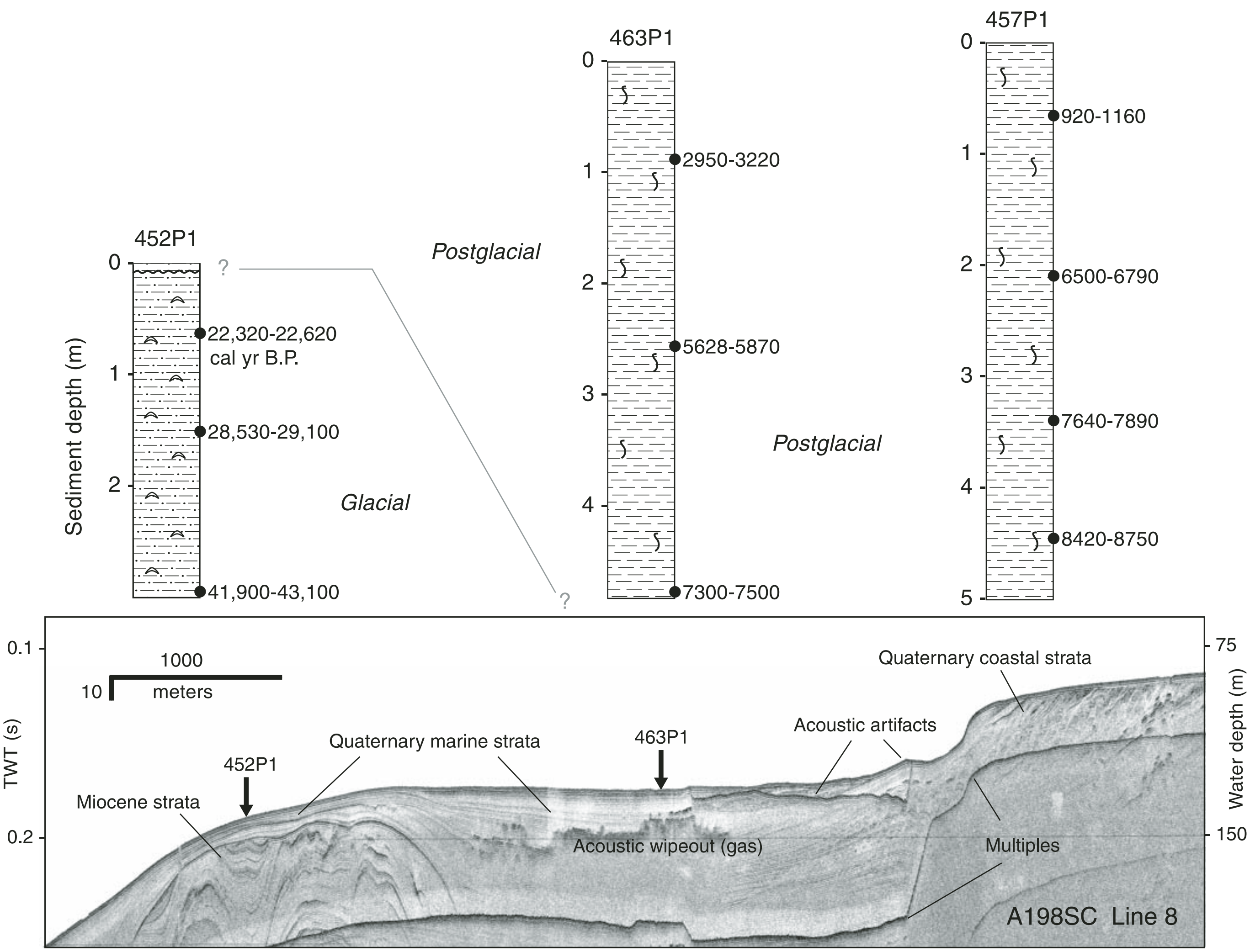

Figure 13. Huntec seismic Line 8 (partial) and core lithology and geochronology for sites in the marginal slope province of Santa Monica Bay. See Figure 4 for sample locations and Figure 9 for lithologic symbols. Line 8 bisects the broad reentrant to Redondo Canyon (see Fig. 4), a bathymetric trap for Quaternary sediments transported across the narrow shelf. Note the presence of shallow, possibly biogenic gas in the subbottom. Cores 463P1 and 457P1 (off the seismic line) record postglacial, hemipelagic sediment accumulation. At these sites, rates of sediment accumulation have decreased through time. Core 452P1 contains strata emplaced during, and prior to, the last glacial interval. The Quaternary strata overly deformed sedimentary rocks of Miocene age (Bohannon et al., 2004). TWT—Two-way travel time.

One possible explanation is that eroded coastal sediment bodies or failed shelf-edge deltas initially provided sediment to the slope and inner basins. Because the ramp-like margin has limited sediment storage capacity, shelf-edge strata eroded during transgression would have been rapidly reworked to deepwater depositional sites, perhaps forming healing-phase deposits on the slope, and increasing rates of hemipelagic sediment accumulation. In some parts of the Southern California Borderland, fan deposition persisted from the LGM to the present highstand (Covault et al., 2007), because the narrow shelf is an ineffective trap for terrigenous sediment. Upon depletion of erosional sources of sediment, and perhaps coupled with a landward shift in the depocenter during transgression, slope and basin accumulation rates would have decreased over time, all other factors equal. The particular response of canyon-fed basins to sea-level rise and coastal inundation appears to depend on the extent to which transgression modifies sediment delivery to canyon heads via entrenched fluvial channels and/or interception of littoral bedload.

Another possible explanation for the 15–10 ka phase of maximum sediment-accumulation rate at sites on the margin is that climate change increased continental runoff and sediment delivery to the coast. Stratigraphic evidence of climate change from Southern California lakes provides strong support for this scenario. Based on proxy records from pluvial Lake Mojave, Wells et al. (2003) estimated that there was a 50%–100% increase in precipitation over the San Bernardino Mountains between 14 and 10 ka, and also that flood discharges of the paleo–Mojave River were two to three times more extreme than those of its

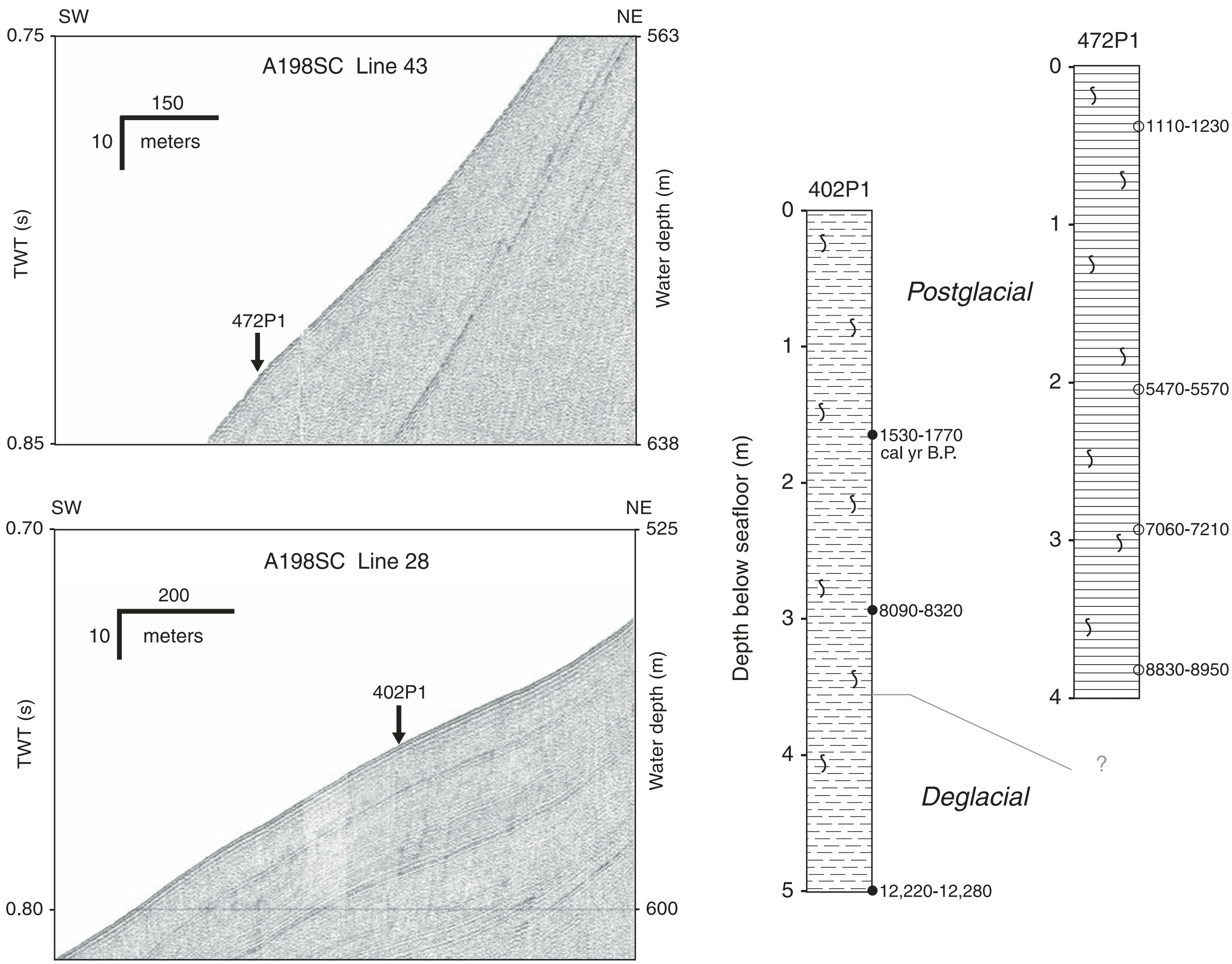

Figure 14. Huntec seismic lines and core lithology and geochronology for sites on the outer marginal slope (Line 43, core 472P1) and outer apron provinces (Line 28, core 402P1) of Santa Monica Bay. See Figure 4 for site locations and Figure 9 for lithologic symbols. In composite, these cores record hemipelagic sediment accumulation during the deglacial and postglacial intervals. At both sites, the sediment lithology and seismic stratigraphy are uniform, with no obvious variability related to transgressive erosion on the surrounding shelf. See text for further discussion. TWT—Two-way travel time.

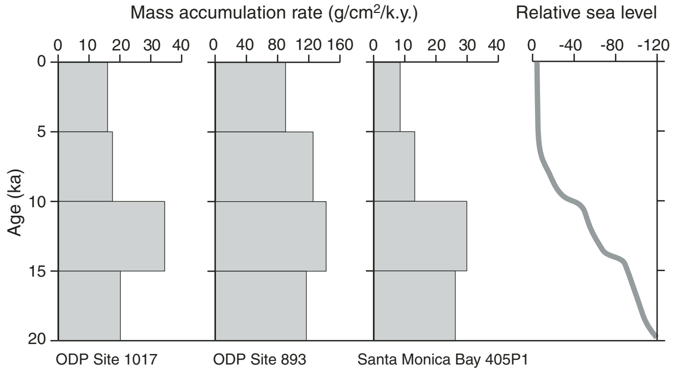

Figure 15. Records of sediment mass accumulation rate for hemipelagic slope (405P1) and inner basin (Ocean Drilling Program [ODP] 1017 and 893) sites off Southern California. The eustatic sea-level curve of Fleming et al. (1998) is shown for reference. At these sites, the interval of maximum accumulation rate occurred during 15–10 ka when the shelf was rapidly inundated by rising sea level. See text for further discussion. Figure modified from Sommerfield and Lee (2004).

modern counterpart. Given the proximity of the San Bernardino Mountains to the watersheds of the Southern California coast, the implication is that continental runoff was equally elevated during this time. This possibility has some support in the record of increased fine-sand burial on the upper slope of Santa Monica Bay during deglacial times.

River discharge retrodictions discussed in a previous section provide independent evidence that fluvial suspended-sediment loads at the coast were significantly larger during deglacial times than during the ensuing postglacial. Mojave pluvial lake phases terminated ca. 9 ka with the onset of drier climates (Wells et al., 2003), a change recorded throughout California by various paleoclimatic proxies (Heusser, 1978; Benson et al., 1998; Mensing, 2001; Barron et al., 2003). On the other hand, the marine sedimentary record of this phenomenon appears to be masked by sedimentological changes related to the terminal phase of rapid transgression (i.e., textural fining and reduced sediment-accumulation rates), which was nearly concordant with hydrologic changes in the watershed. In short, we cannot rule out that eustatic and climatic factors were equally effective in modulating sediment delivery to the Southern California shelf during deglacial and postglacial times.

CONCLUSIONS AND SUMMARY POINTS

Below, we offer the following points as key findings and interpretations of this study:

(1) The volume of postglacial sediment sequestered on the Southern California shelf between Point Conception and Dana Point varies with regime variables such as sediment-source proximity and delivery rates, as well as topographic-bathymetric conditions conductive for sediment trapping or bypass. The Santa Barbara cell contains the largest mass of sediment ($32–42 \times 10^9$ metric tons) in the study area, most of which is present at the eastern end between Santa Barbara and Hueneme Canyon. Between Santa Barbara and Point Conception to the west, the shelf is a bypass zone with sediment accumulations generally less than 10 m in thickness. Approximately 12 km^3 of sediment is sequestered within the eastern Santa Barbara cell alone, a volume equivalent to one third of the total amount of postglacial sediment on the greater Southern California shelf (30.8 km^3). The large quantity of sediment supplied by the Ventura and Santa Clara Rivers distinguishes this segment of shelf from others. Inclusive of the shelf and upper slope (to 500 m water depths), the mass of postglacial sediment sequestered within the Santa Monica cell is $\sim 6–8 \times 10^9$ metric tons, the smallest mass among the three cells considered in this study. Sedimentary cover is thick on the Malibu shelf and adjacent to the head of Redondo Canyon, intermediate on the Santa Monica shelf, and thin to nonexistent over the remaining shelf province. By comparison, the San Pedro cell contains the second largest quantity of postglacial sediment in the study area ($8–11 \times 10^9$ metric tons), most of which is present on the eastern Palos Verdes shelf and on the outer San Pedro shelf.

(2) River discharge retrodictions based on the cross-sectional geometry of seismically imaged paleochannels of the Santa Clara River, Ballona Creek, the Los Angeles River, and the San Gabriel River provide insight on sediment delivery to the coast during late glacial to early deglacial times. The highest and lowest paleodischarges are indicated for the ancestral Santa Clara River ($383–511 \times 10^3$ m^3/s) and Ballona Creek ($8.3–19 \times 10^3$ m^3/s), respectively, and for all rivers, the absolute magnitude of the estimate peak paleoflow is at least one order of magnitude larger than modern (measured) peakflow values. Retrodicted peak sediment loads range from a high of 2000–3200 metric tons/s for the ancestral Santa Clara River to a low of 5–18 metric tons/s for the former Ballona Creek, again, an order of magnitude or more larger than contemporary values. These significantly larger discharges are a consequence of the relatively large cross-sectional area of the paleochannels, which would have been in equilibrium with climatically intensified continental runoff during the deglacial period. Among coastal cells the parallel between postglacial shelf-sediment mass and retrodicted sediment load suggests that the relative quantity of sediment sequestered was largely a function of fluvial sediment efflux, though tectonism and antecedent topography influenced spatial patterns of sediment accumulation.

(3) The post–LGM transgressive history of the margin preserved by shelf and slope strata is distinct among the shelf, apron, and marginal slope morphologic provinces. Within the shelf province of Santa Monica Bay, transgression is recorded by characteristic ravinement

surfaces and an upsection transition from coastal (or nonmarine) to marine sediment facies. The sedimentary record indicates that depositional conditions analogous to the modern shelf environment were established by 8–9 ka in Santa Monica and San Pedro Bays, or perhaps earlier, if the shelf experienced uplift. Within the Santa Monica apron province, transgression is evinced by an initial increase in grain size, presumably on account of resedimented shelf sands and coarse silts, followed by decreases in mean grain size and accumulation rate. The geometry and stratification of the apron sediment blanket suggests that sediment-gravity flows generated on the shelf are at least one mechanism of transport and deposition. At several apron sites, linear sediment-accumulation rates decreased by at least a factor of three from deglacial to postglacial times, a change that parallels trends in hemipelagic sedimentation recorded at sites in the inner borderland basins. Downcore sedimentology and ^{14}C age dates indicate that accretionary slope gullies in Santa Monica Bay were active conduits for dilute debris flows up to ca. 13 ka, after which began the present phase of hemipelagic blanketing of gully topography. In contrast to the shelf and apron provinces, deglacial–postglacial sediment accumulation within the marginal slope of Santa Monica Bay was outwardly invariant during transgression. Downcore sedimentology and acoustic facies of marginal slope strata display none of the characteristic signatures of transgression, perhaps because these areas were somewhat removed from the shelf. Santa Monica Bay is presently in a late-transgressive to early-highstand stage of sedimentation. Consistent with the accommodation-dominated shelf type, postglacial transgressive strata have been blanketed by marine muds in some areas, but coastal progradation and development of a highstand systems tract have yet to occur.

(4) The sedimentary response of the Southern California shelf and slope to conditions of the last deglacial and postglacial transgression is comparable to that observed on tectonically passive margins, despite active tectonism in the region. However, results of this and related studies make clear that the general sequence stratigraphic model (in which sedimentary cycles are driven by eustacy) is not well suited to basins with narrow shelves fed by distributed sources of fluvial and coastal sediment. In the present study area, one deviation from the general model is the phase of maximum hemipelagic sediment-accumulation rate during the early transgression (15–10 ka) rather than at lowstand (20–18 ka). This departure can be explained by local basin factors: (1) the ramp-like shape of the margin, limiting sediment storage on shelves; (2) transgressive erosion and downslope redistribution of coastal sediments; and (3) deglacial climatic conditions conducive for increasing fluvial sediment production in the watershed and delivery to the coast.

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