Coarse-grained sediment delivery and distribution in the Holocene Santa Monica Basin, California: Implications for evaluating source-to-sink flux at millennial time scales

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ABSTRACT

Utilizing accumulations of coarse-grained terrigenous sediment from deep-marine basins to evaluate the relative contributions of and history of controls on sediment flux through a source-to-sink system has been difficult as a result of limited knowledge of event timing. In this study, six new radiocarbon (^{14}C) dates are integrated with five previously published dates that have been recalibrated from a 12.5-m-thick turbidite section from Ocean Drilling Program (ODP) Site 1015 in Santa Monica Basin, offshore California. This borehole is tied to high-resolution seismic-reflection profiles that cover an 1100 km^2 area of the middle and lower Hueneme submarine fan and most of the basin plain. The resulting stratigraphic framework provides the highest temporal resolution for a thick-bedded Holocene turbidite succession to date, permitting an evaluation of source-to-sink controls at millennial (1000 yr) scales.

The depositional history from 7 ka to present indicates that the recurrence interval for large turbidity-current events is relatively constant (300–360 yr), but the volume of sediment deposited on the fan and in the basin plain has increased by a factor of 2 over this period. Moreover, the amount of sand per event on the basin plain during the same interval has increased by a factor of 7. Maps of sediment distribution derived from correlation of seismic-reflection profiles indicate that this trend cannot be attributed exclusively to autogenic processes (e.g., progradation of depocenters). The observed variability in sediment accumulation rates is thus largely controlled by allogenic factors, including: (1) increased discharge of Santa Clara River as a result of increased magnitude and frequency of El Niño–Southern Oscillation (ENSO) events from ca. 2 ka to present, (2) an apparent change in routing of coarse-grained sediment within the staging area at ca. 3 ka (i.e., from direct river input to indirect, littoral cell input into Hueneme submarine canyon), and (3) decreasing rates of sea-level rise (i.e., rate of rise slowed considerably by ca. 3 ka). The Holocene history of the Santa Clara River–Santa Monica Basin source-to-sink system demonstrates the ways in which varying sediment flux and changes in dispersal pathways affect the basinal stratigraphic record.

INTRODUCTION

Accumulations of terrigenous sediment in deep-marine basins commonly represent the terminal position for source-to-sink sediment flux across a continental margin. The sedimentary succession in the sink records the interactions of external, or allogenic, controls (e.g., eustasy, climatic conditions, tectonic activity) and intrinsic, or autogenic, dynamics (e.g., sediment gravity-flow processes and development of depositional relief). Sedimentary basin fills have long been utilized to infer sedimentary flux for ancient source-to-sink systems because of their preservation potential (e.g., Fisher and McGowen, 1967; Allen and Allen, 1990; Einsele et al., 1996; Hovius, 1997; Syvitski et al., 2003). Over relatively long time scales (i.e., ≥100 k.y.), limited geochronometric precision combined with a lack of context preclude a comprehensive assessment of the interacting factors that control rates of sediment production, transfer, and deposition.

Analyses of Holocene source-to-sink systems provide explicit information about forcing factors and initial conditions, permitting a well-constrained evaluation of controls. Marine records generally provide better estimates of total sediment flux and variability over millennial time scales than onshore components of the source-to-sink system (Einsele et al., 1996; Hebbeln et al., 2007). The record of sedimentation in the staging area (i.e., coastal plain, delta front, beach, etc.) is inherently less complete as a result of relatively low storage capacity, short residence times, and fluctuating routing pathways for the sediment (e.g., Phillips et al., 2007). Furthermore, the occurrence and preservation of dateable material along coarse-grained routing pathways in the staging area are limited. Thus, the aim of this study was to investigate the patterns, rates, and controls on deep-marine turbidite system development in Santa Monica Basin during the last ~7000 yr. Eleven radiocarbon ages from the uppermost 12.5 m at Ocean Drilling Program (ODP) Site 1015, Santa Monica Basin (offshore southern California), constrain the timing of sedimentation. These data represent the highest-resolution chronology for a thick-bedded turbidite section to date. Sediment storage in floodplain and coastal plain areas for the Santa Clara River is small relative to its total flux (Inman and Jenkins, 1999), thus increasing the proportion of total sediment transferred to the sink. Therefore, the terrigenous archives in Santa Monica Basin are the best record for estimating total flux of coarse-grained sediment from the source area.

Many conceptual models explaining the origin of deep-marine stratigraphic architecture have been derived from outcrop information (e.g., Pickering and Hilton, 1998; Campion et al., 2000; Steel et al., 2000; Gardner et al., 2003; McCaffrey et al., 2002; Hickson and Lowe, 2002; Anderson et al., 2006). Many of

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these outcrops are remnants of deep-marine basins similar to Santa Monica Basin with respect to their source-to-sink characteristics (i.e., small drainage basin size, high relief in nearby source area, highly fluctuating river discharge, narrow shelf width, moderate to high tectonic activity, etc.; Mutti et al., 2003). However, many of the conceptual models derived from such systems have been used to interpret similar architectural patterns observed in passive-margin systems (e.g., Abreu et al., 2003; Deptuck et al., 2003), in which short-term variability in sediment flux might be minimized, particularly with increasing distance down system (e.g., Flood et al., 1991; Pirmez and Flood, 1995). Potential misapplications of outcrop analogs have been discussed at length by previous turbidite researchers (e.g., Mutti and Normark, 1987; Mutti and Normark, 1991). Thus, an additional aim of this study is to examine the signature of allogenically driven sediment-flux variability at a relatively high resolution (i.e., short duration [7 k.y.]; thin succession [12.5 m]).

GEOLOGIC SETTING AND PREVIOUS WORK

Tectonic Setting of the California Continental Borderland

The present physiography of the tectonically active southern Californian margin is dominated by features related to the San Andreas fault system (Fig. 1). The California Continental Borderland is the offshore segment of the transform margin extending from Point Conception just west of Santa Barbara to south of the U.S.–Mexico border. The Borderland is characterized by extensive ridge and basin morphology that occurred as a result of oblique extension starting in the early Miocene (Lonsdale, 1991). Since ca. 5 Ma, the northwest-southeast–trending normal faults in the northern Borderland and Western Transverse Ranges have been reactivated as reverse faults, oblique thrusts, and strike-slip faults as a result of regional transpression (Crouch and Suppe, 1993; Vedder, 1987; Sorlien et al., 2006). Active west-striking faults, including Dume, Santa Monica, and Malibu Coast faults, separate the high-relief onshore Western Transverse Ranges from the offshore basins of the northern Borderland (Sorlien et al., 2006).

Santa Clara River Sediment Dispersal System

Rivers are the primary source of coarse-grained terrigenous sediment to the California Continental Borderland basins, contributing ~90% of the sand in the littoral cells (in historical times) (Brownlie and Taylor, 1981; Inman and Jenkins, 1999). Sediment production from Transverse Ranges rivers is twice that of the Coast Ranges to the north and an order of magnitude greater than the Peninsular Ranges to the south (Inman and Jenkins, 1999). Of the Transverse Ranges river systems, the Santa Clara River is the primary sediment source to the northern Borderland, including the Santa Monica Basin (Fig. 1) (Schwalbach and Gorsline, 1985; Inman and Jenkins, 1999; Warrick, 2002; Warrick and Milliman, 2003). The relatively soft and easily eroded Tertiary sedimentary rocks of the Transverse Ranges, combined with active tectonism and high relief, provide abundant sediment to the Santa Clara River watershed (Inman and Jenkins, 1999). The Santa Clara River watershed delivers three times more sediment to the coast and offshore basins than the Los Angeles and San Gabriel Rivers and ~30 times as much as most other Borderland drainage basins (Warrick and Farnsworth, 2009). Studies of historical Santa Clara River sediment flux have also shown that the system is dominated by infrequent events; data from the past 72 yr indicate that over 50% of the sediment load was produced during only 5 yr (Warrick, 2002; Warrick and Milliman, 2003; Warrick and Farnsworth, 2009). When combined with the adjacent watersheds of the Ventura River and Calleguas Creek, the Santa Clara River still accounts for >70% of total annual sediment flux to the Borderland offshore area (Fig. 1) (Warrick and Farnsworth, 2009). The proportional relationships among southern California rivers noted here are likely influenced by anthropogenic effects (i.e., dams); the magnitude of historical Santa Clara River sediment flux, however, is inferred to be close to natural levels because of its relatively underdeveloped character (Willis and Griggs, 2003). The total annual sediment flux of the Santa Clara River is within the same order of magnitude as other high-sediment-flux rivers along the western margin of the United States (e.g., Eel River; Sommerfield and Nittrouer, 1999).

Santa Barbara Littoral Cell and Continental Shelf

The Holocene continental shelf directly seaward of the Santa Clara River mouth represents the Pleistocene Santa Clara River delta that developed during the Last Glacial Maximum (LGM) sea-level lowstand (Greene et al., 1978; Dahlen, et al., 1990). Postglacial transgression drowned this area, leaving many of the conduits connecting coarse-grained terrigenous material on the delta to Santa Barbara and Santa Monica Basins stranded and abandoned at the shelf edge (Normark et al., 1998, 2006). The Holocene Santa Barbara littoral cell, the longest in California, extends ~150 km from Point Conception to Mugu Canyon and transports coastal sediment from west to east (Fig. 1; Masters, 2006). The head of Hueneme submarine canyon intersects the cell, providing a conduit for coarse-grained sediment to Santa Monica Basin. Coarse-grained sediments that do not get funneled down Hueneme Canyon and continue eastward, as well as clastic material that comes from more easterly inputs (e.g., Calleguas Creek), feed Mugu or Dume submarine canyons or remain in the littoral cell (Figs. 1 and 2). The sediment source areas for both the Santa Barbara littoral cell and the Santa Clara River are within the Western Transverse Ranges (Critelli et al., 1997), and this hampers effective discrimination of staging areas from compositional data (especially at bed-scale resolution).

Santa Monica Basin and Hueneme Submarine Fan

Santa Monica Basin is a 2000 km^2 northwest-southeast–trending basin (900 m greatest water depth) bounded by the Santa Cruz–Catalina submarine ridge to the southwest, the narrow (< 10 km) continental shelf to the north and northeast, and Redondo Knoll to the southeast (Fig. 2). Unlike Borderland basins to the south (e.g., Normark et al., 2006; Covault et al., 2007; Normark et al., 2009), Santa Monica Basin is a closed basin with a ponded Quaternary fill (Normark et al., 2006). The stratigraphy of closed basins permits a better evaluation of source-to-sink flux because coarse-grained sediment gravity flows that enter Santa Monica Basin deposit their full load there (i.e., there is no significant bypass to more distal basins).

The Hueneme Fan, located in the western part of Santa Monica Basin, is one of the best-known and well-studied sand-rich submarine fans in the world. Pioneering work by Gorsline and Emery (1959) and Junger and Wagner (1977) documented the occurrence and significance of gravity flow–delivered terrigenous sediment to Borderland basins. Nardin (1981, 1983) first integrated seismic-reflection profiles and piston cores to map the distribution of coarse sediment in Santa Monica Basin. The most recent depositional history (past ~500 yr) has been evaluated from numerous box cores (e.g., Reynolds, 1987; Huh et al., 1990; Christensen et al., 1994; Gorsline, 1996). Conventional bathymetric charts and Geological Long-Range Inclined Asdic (GLORIA) side-scan sonar surveys (Edwards et al., 1996) have provided a view of the basin-scale morphology and sediment distribution. Normark et al. (1998), using sleeve gun

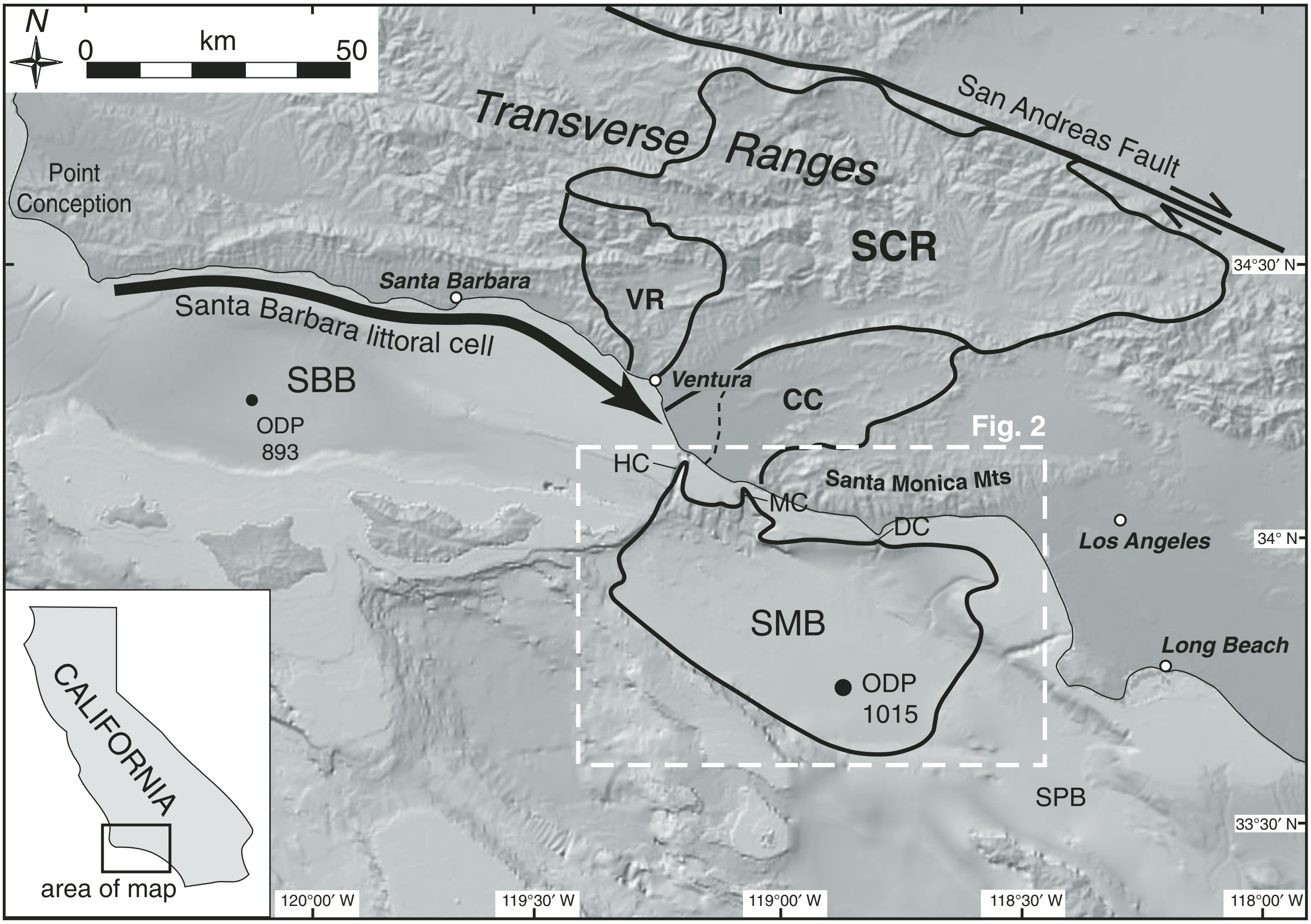

Figure 1. Combined topographic and bathymetric map of Western Transverse Ranges (onshore) and northern California Continental Borderland (offshore) of southern California. Onshore drainage basin source areas: SCR—Santa Clara River; CC—Calleguas Creek; VR—Ventura River. Dashed line between Santa Clara River and Calleguas Creek represents drainage basin boundary before ca. 2 ka. Terrigenous sediment staging areas: HC—Hueneme Canyon; MC—Mugu Canyon; DC—Dume Canyon. Basinal sediment sinks: SBB—Santa Barbara Basin; SMB—Santa Monica Basin; SPB—San Pedro Basin. Refer to Figure 2 (dashed white box) for more details about Santa Monica Basin and data used. Topography and bathymetry data are from the Marine Geoscience Data System (MGDS); map was created with GeoMapApp© tool. ODP—Ocean Drilling Program.

seismic-reflection data (~20 m vertical resolution to a depth of as much as 1 s below seafloor), developed a chronology of sedimentation patterns for Hueneme Fan and nearby, smaller Dume Fan for the last ~150 k.y. Piper et al. (1999) mapped the sedimentary features of the upper 20–80 ms (milliseconds) with very high vertical resolution (<1 m) using a deep-tow boomer reflection profiling system.

General Depositional History since the Last Glacial Maximum

Normark et al. (2006) offered a comprehensive view of sedimentation among the separate canyon and fan systems of Santa Monica Basin over the last glacial cycle (32 ka–present). Sea level has risen nearly 130 m since the Last Glacial Maximum (18–25 ka) lowstand, to near its current position at ca. 7 ka (Lambeck and Chappell, 2001). Sea level continued to rise at a much slower rate from 7 to ca. 3 ka, and it has been at a near stillstand since 3 ka (Lambeck and Chappell, 2001; Masters, 2006). During the lowstand, when the shoreline was at or near the modern shelf edge, several feeder canyons delivered coarse-grained sediment from the Santa Clara River delta directly to the deep water (Fig. 2) (Dahlen et al., 1990; Normark et al., 1998, 2006). During postglacial transgression, the Hueneme and Mugu Canyons maintained a connection with the shoreline as they eroded headward, while the others were abandoned (Piper et al., 1999; Sommerfield and Lee, 2003; Normark et al., 2006). The focus of this study is the sediment-flux history from 7 ka to present, and therefore this study is limited to the transfer through Hueneme Canyon and, to a much lesser extent, Mugu and Dume Canyons, which have been the primary active conduits for coarse sediment during the middle to late Holocene (Fig. 2). Dume submarine fan is a small slope apron–type fan that is well north of the detailed mapping presented in this study. Although Mugu submarine canyon was active in the Holocene, its associated submarine fan deposits have been interpreted to be less voluminous during this period (Normark et al., 2006).

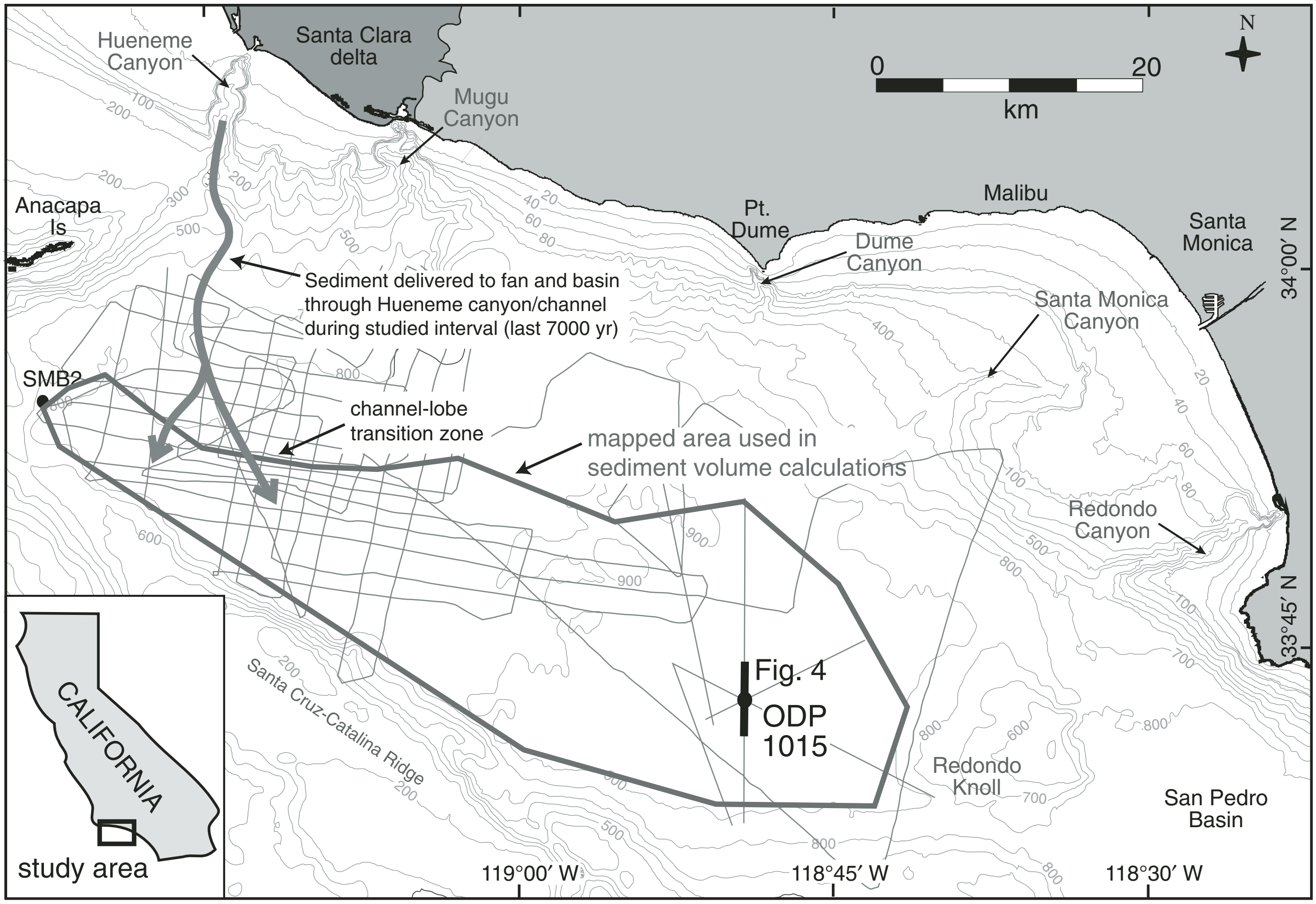

Figure 2. Map of Santa Monica Basin showing bathymetry (in m), location of major feeder canyons, grid of two-dimensional (2-D) seismic-reflection profiles used in this study (light gray lines), and location of Ocean Drilling Program (ODP) Site 1015 cores. Black polygon represents area of middle and lower fan and basin plain where sediment distribution was mapped and sediment volumes were calculated. See Figure 1 for regional source-to-sink context. Figure was adapted from Normark et al. (2006).

DATA AND APPROACH

ODP Site 1015 and Radiocarbon Dates

Ocean Drilling Project (ODP) Site 1015 (33°42.925′N, 118°49.185′W) was drilled in 1996 (Shipboard Scientific Party, 1997) to complement the marine sediment archive from ODP Site 893 in adjacent Santa Barbara Basin (e.g., Kennett and Venz, 1995). ODP Site 1015 consists of two holes, 1015A and 1015B, drilled ~100 m apart on the basin plain and deepest part of Santa Monica Basin (900 m water depth) (Fig. 2). This study focuses on the uppermost 12.5 m of the succession, which encompasses the last 7000 yr. Radiocarbon dates presented in Normark et al. (2006) and Normark and McGann (2004) are supplemented by six additional dates for a total of 11 dates over the 12.5-m-thick succession (Table 1). Integration of new dates reported here from Site 1015 Hole A permit bed by bed correlation with published dates from Site 1015 Hole B (Normark et al., 2006; Normark and McGann, 2004). Benthic foraminifera were sampled from mud layers presumed to be hemipelagic in origin and dated using accelerator mass spectrometry (AMS) ^{14}C at the National Ocean Sciences AMS (NOSAMS) Facility at the Woods Hole Oceanographic Institution. Table 1 gives both reservoir-corrected and calibrated ages; the latter are used for calculations of recurrence interval and sediment accumulation rates. Ages were calculated using the accepted half-life of ^{14}C of 5568 yr (Stuiver and Polach, 1977). The original measurements were obtained by a ^{14}C/^{12}C ratio and corrected for isotope fractionation by normalizing for δ^{13}C by NOSAMS. All raw radiocarbon ages were younger than 22 ka and therefore converted to calibrated ages using the CALIB 5.0.1 software (Stuiver et al., 1998, 2005). A reservoir age of 1750 yr was chosen for the benthic foraminiferal samples following Mix et al. (1999).

A composite log for the upper 12.5 m of ODP Site 1015 was generated with the additional age control and a refined core description by the authors (Fig. 3). This new core description is at a higher resolution than currently available from ODP visual core description data (Shipboard Scientific Party, 1997), and thus it is useful for more detailed sedimentologic interpretations. The uppermost ^{14}C dates from ODP 1015B, which are 25 cm apart in the core, show a minor age reversal (Table 1). For this study, the upper date (OS-35811) was used for subsequent rate calculations based on the possibility of minor geochemical alteration of OS-63127 suggested by the presence of gypsum crystals in the sample (Schnitker et al., 1980). Additionally, if errors of the two ages are considered, the discrepancy between the two dates is only 83 yr, indicating that they are nearly the same. The composite log is tied to the high-resolution seismic-reflection data, providing

TABLE 1. RADIOCARBON AGE INFORMATION FROM ODP SITE 1015

NOSAMS Accession number	Submitter Identification	Depth (mbsf)	Description	δ^{13}C (‰)	Age (yr)	Age error (yr)	Age (yr, reservoir corrected)	Calendar age (yr B.P.)
ODP 1015 B[*]								
OS-35811	ODP 1015B, 002H 02W, 55–57 cm	4.35	Mixed benthic foraminifera	–0.66	3430	±45	1680	1654
OS-63127[†]	ODP 1015B, 002H, 02W, 82–84 cm	4.62	Mixed benthic foraminifera	–1.93	3300	±30	1550	1496
OS-35835	ODP 1015B, 002H 03W, 144–146 cm	6.74	*Uvigerina* sp.	–0.46	3850	±40	2100	2170
OS-35836	ODP 1015B, 002H 04W, 101–103 cm	7.81	*Uvigerina* sp.	–0.47	4720	±30	2970	3246
OS-35837	ODP 1015B, 002H 06W, 12–14 cm	9.92	*Uvigerina* sp.	–0.61	5530	±35	3780	4268
OS-39187	ODP 1015B, 002H, 07W, 55–57 cm	11.68	Mixed benthic foraminifera	0.65	6940	±70	5190	5990
ODP 1015 A[†]								
OS-58243	ODP 1015A, 001H, 01W, 15–17 cm	0.16	Mixed benthic foraminifera	–0.6	2200	±30	450	481
OS-58244	ODP 1015A, 001H, 02W, 65–67 cm	2.16	Mixed benthic foraminifera	–1.72	2510	±30	760	703
OS-58739	ODP 1015A, 001H, 04W, 46–48 cm	4.97	Mixed benthic foraminifera	–0.86	3470	±35	1720	1707
OS-61320	ODP 1015A, 001H, 05W, 6–8 cm	6.07	Mixed benthic foraminifera	–1.0	3520	±45	1770	1763
OS-61198	ODP 1015A 002H, 02W, 93–95 cm	9.44	Mixed benthic foraminifera	–0.67	5450	±35	3700	4150
OS-58245	ODP 1015A, 002H, 04W, 92–94 cm	12.44	Mixed benthic foraminifera	–0.66	7770	±35	6020	6902

[*] Ages from Ocean Drilling Program (ODP) Site 1015B (excluding OS-63127) were originally reported in Normark and McGann (2004) and Normark et al. (2006) as raw and reservoir-corrected ages; this study uses calibrated ages (yr B.P.). Depth is in meters below seafloor (mbsf).

[†] Samples collected and dated for this study.

an exceptionally well-constrained stratigraphic framework to evaluate sediment flux to the basin. In addition to radiocarbon ages at ODP Site 1015, ages from piston core SMB2 along the southwestern basin margin (Normark and McGann, 2004) further constrain the timing for the mapped sedimentary packages (Fig. 2).

Seismic-Reflection Data

This study utilizes two-dimensional (2-D) seismic-reflection data acquired by the Geological Survey of Canada and the U.S. Geological Survey Marine Earthquake-Hazards Project. These data, which were originally reported by Piper et al. (1999) and more recently by Normark et al. (2006), are analyzed here within the context of the aforementioned new and recalibrated radiocarbon age control. High-resolution seismic-reflection data were obtained using a Huntec DTS boomer system (Huntec Ltd., Toronto, Canada), towed ~150 m below the sea surface with heave and depth compensation. Acoustic signals were received on a 15-ft-long (4.5 m), single-channel, 10-element, oil-filled streamer (Benthos MESH 15/10P; Benthos Inc., North Falmouth, Massachusetts, USA) towed behind the fish containing the boomer source. Signals were filtered at 500–10 kHz with spreading-loss gain recovery. The source was operated at 500 J output. The signal contains a broad-frequency bandwidth (up to 6 kHz), which yields an optimal vertical resolution of <1 m and imaging up to 100 m below the seafloor. Spacing between lines averages between 2 and 3 km and is as close as 0.7 km in some areas (Fig. 2).

The stratigraphic framework from Piper et al. (1999) and Normark et al. (2006) has also been refined with additional seismic-reflection horizons as well as remapping in some areas (Table 2). Detailed mapping is focused on areas of net turbidity-current deposition of the middle and lower Hueneme Fan and most of the basin plain (Fig. 2). The upper fan area is excluded in this analysis because of the erosional nature of the channel-levee system (Normark et al., 1998; Piper et al., 1999) and associated difficulty in tracking marker horizons at such high spatial and temporal resolutions. Furthermore, because sedimentation has remained active throughout the Holocene, there are no basinwide condensed intervals, and the hemipelagic horizons identified in the ODP Site 1015 core may correlate to sandier deposits in the channel-lobe transition area (Fig. 2). A thorough analysis of the acoustic facies is presented in Piper et al. (1999).

SEDIMENT DISTRIBUTION ON MIDDLE AND LOWER HUENEME FAN AND SANTA MONICA BASIN PLAIN

The high vertical resolution of the seismic-reflection data (<1 m) provides a tie to the sediment observed in the ODP Site 1015 cores (Fig. 4). The thicker (~1 m) sand beds in the upper part of the section, for example, are individually resolved. Although numerous prominent seismic-reflection horizons are evident in the relatively low-relief basin plain stratigraphy at ODP Site 1015, five horizons were chosen because they were correlatable over a large area (1100 km^2) of Santa Monica Basin (Fig. 2). The resulting stratigraphic framework consists of five mappable intervals of comparable thickness (Fig. 3). Thicknesses were calculated using a time-depth conversion based on a compressional sound velocity of 1580 m/s, which is typical for near-surface marine sediment of this type and water depth in the California Borderland (Hamilton et al., 1956). The correlation and mapping within this stratigraphic framework are summarized by a series of isopach maps (Fig. 5). These maps show thickness distribution for the middle to lower Hueneme Fan and Santa Monica Basin plain for the past 7 k.y. This particular area (1100 km^2) was mapped because of adequate coverage of seismic-reflection data combined with areas of high confidence in correlating seismic marker horizons.

The activity of the Hueneme canyon-channel system as a conduit for sediment to Santa Monica Basin during the Holocene is indicated by the position of depocenters (i.e., areas of greatest thickness) at the terminus of the channel at the upper–middle fan boundary (Figs. 5 and 6). In detail, the sediment distribution maps reveal an evolution of laterally shifting depocenters. The depocenters for intervals 1 and 2 (6.90–4.15 ka and 4.15–1.76 ka, respectively)

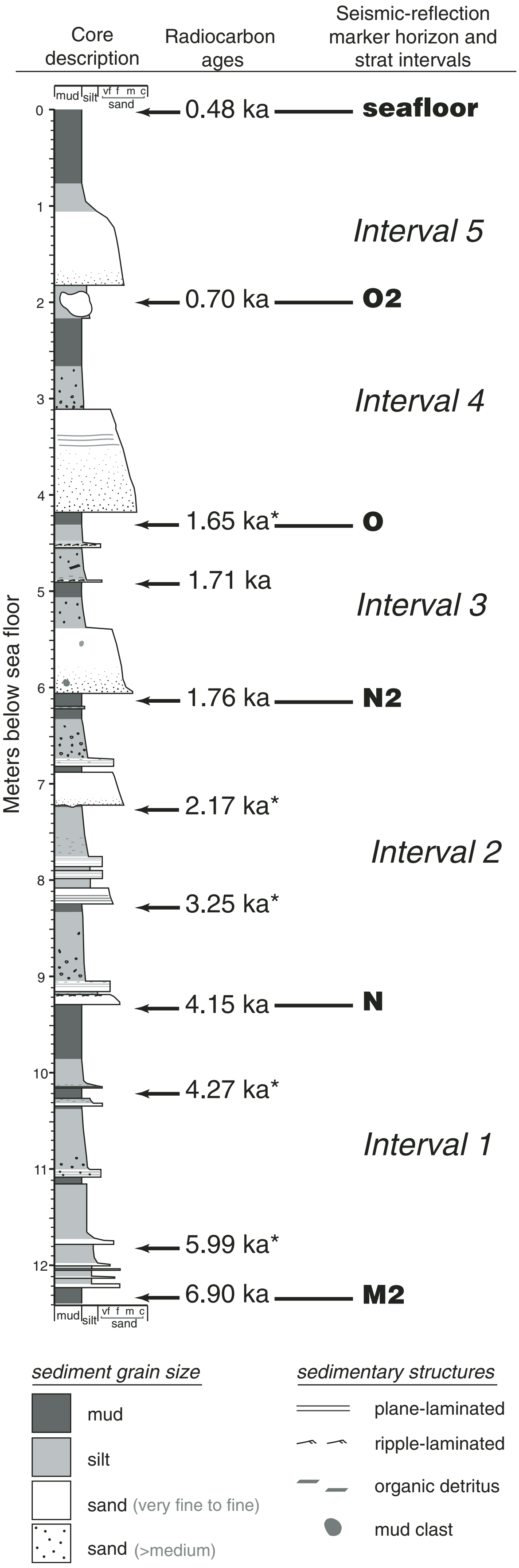

Figure 3. Description of uppermost 12.5 m of Ocean Drilling Program (ODP) Site 1015. Sediment log is from redescription of ODP 1015A, and it shows radiocarbon ages and seismic-reflection marker horizons. Asterisks by radiocarbon age denote samples from ODP 1015B (100 m away) that were taken to confirm correlation and generate this composite section. Samples of foraminifera (for radiocarbon) were taken from the finest-grained intervals present (presumed to be hemipelagic). See Table 1 for radiocarbon sample information. Refer to Figure 2 for location of core and track-line survey of seismic-reflection data. Tie to seismic-reflection data is shown in Figure 4.

TABLE 2. DEPTH AND AGE OF SEISMIC-REFLECTION HORIZONS

Depth in composite ODP 1015 core (mbsf)*	Age (ka)	Existing horizon[†]	New horizon mapped in this study
0.00	0.00	seafloor	
2.16	0.70	–	O2
4.35	1.65	O	
6.12	1.76	–	N2
9.30	4.15	N	
12.44	6.90	–	M2

*ODP—Ocean Drilling Program; mbsf—meters below seafloor.
[†]From Normark et al. (2006).

are positioned at the middle fan–lower fan transition, ~3 km eastward and slightly basinward of the current mouth of Hueneme submarine channel (Figs. 5A and 5B). Interval 3 (1.76–1.65 ka) is the thinnest and has two depocenters, one in the same general position as underlying intervals and one ~5 km to the west of the current mouth of the Hueneme submarine channel (Fig. 5C). Finally, the depocenters for intervals 4 and 5 (1.65–0.70 ka and 0.70 ka–present, respectively), are positioned at the channel-lobe transition zone for the modern Hueneme submarine channel (Figs. 5D and 5E).

The mostly incoherent, high-backscatter acoustic facies in the middle fan area is representative of the sandiest part of the fan, and it reflects lobe deposition at or near the mouth of Hueneme submarine channel (see Piper et al., 1999). The high-density of cross-lines and ties to radiocarbon-dated cores on both sides of the sandiest part of the fan (SMB2 to the west and ODP Site 1015 to the east; Fig. 2) constrain correlations through this poorly resolved part of the survey. The certainty of correlations in the lower fan area to the basin plain is much higher, likely as a result of widespread mud deposition (and little erosion) between successive events.

SEDIMENT VOLUMES AND ACCUMULATION RATES IN SANTA MONICA BASIN FROM 6.9 KA TO PRESENT

Sediment Volume Calculations

Bulk volume for each of the five stratigraphic intervals was determined using the area and corresponding thickness from the isopach maps (Fig. 5). An area of the fan and basin plain (1100 km^2) common to all five stratigraphic intervals was used to maintain consistency among volume calculations (Fig. 2). Table 3 shows the bulk volume (km^3), sediment volume (km^3), and sediment mass (tons) for each interval and in total. An average porosity of 38% was calculated

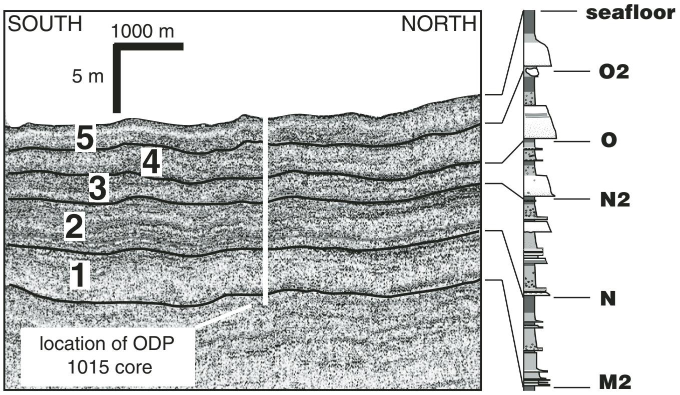

Figure 4. Composite Ocean Drilling Program (ODP) Site 1015 core log tied to Huntec high-resolution seismic-reflection data. See Figure 3 for detailed view of core and stratigraphic position of radiocarbon dates. Refer to Figure 2 for location of core and track-line survey of seismic-reflection data.

from ODP Site 1015 core data (bulk density) for these shallow sediments (Shipboard Scientific Party, 1997), and this value was used to convert bulk volume to sediment volume; a density of 2.65 g/cm^3 was used to convert sediment volume to sediment mass (expressed in tons). The total sediment volume accumulated in Santa Monica Basin in 7000 yr is 8.8 km^3 (~26 billion tons).

Timing and Rates of Sediment Accumulation

The exceptional temporal constraints afforded by the new radiocarbon dates (Fig. 3) permit an evaluation of accumulation rates of terrigenous sediment during the middle to late Holocene (7 ka to present). The sediment accumulation record in Santa Monica Basin during this period is a combination of relatively continuous hemipelagic deposition and episodic (and effectively instantaneous) sediment gravity-flow deposition. The deposits at ODP Site 1015 indicate that the majority of the succession (at least 65%) is turbiditic (Fig. 3). The magnitude of turbidity-current events examined in this study is large enough to produce recognizable turbidite beds in the ODP Site 1015 core (>1–2 cm and typically coarser than silt; Fig. 3). The much smaller events, expressed as very thin (<1 cm) silt layers that have been documented from box cores (e.g., Huh et al., 1990; Christensen et al., 1994; Gorsline, 1996), are excluded from this analysis.

The core to seismic-reflection tie (Fig. 4) provides an opportunity to evaluate accumulation rates based on the calculated volumes (Table 3). The average accumulation rate for the total duration of the five stratigraphic intervals (6.9 k.y.) is ~1.3 km^3/k.y., whereas rates for individual intervals range from less than 1 km^3/k.y. to greater than 12 km^3/k.y. In terms of sediment mass, the entire succession averages ~3.7 million tons/yr, which is comparable to measurements of sediment flux at the Santa Clara River mouth during historical times (3.2 million tons/yr; Warrick and Farnsworth, 2009).

The change in volume (as determined from the mapped intervals) from interval to interval is proportional to the change in thickness (as determined from ODP Site 1015) from interval to interval (Fig. 7). Thus, the ODP Site 1015 record is an adequate representation of sediment flux variability in the basin as a whole, permitting more detailed analysis of accumulation rates derived solely from the core. An analysis of sedimentation rates from irregular time series has been shown to introduce a bias such that shorter measured time intervals result in higher sediment accumulation rates and vice versa (Sadler, 1981). The simplest solution to this sampling bias is to compare intervals of equal duration. The succession at ODP Site 1015 was therefore subdivided into two sections; one older section from 6.90 ka to 3.25 ka (3.65 k.y. duration), and a younger section from 3.25 ka to present (3.25 k.y. duration) (Table 4). Total sediment accumulation rates increase by a factor of 2 (from 1.14 to 2.55 m/k.y.), and average thickness of sand per turbidity-current event increases by a factor greater than 7 (from 4 cm to 30 cm) from the older to the younger section (Table 4). A summation of the intervals denoted as hemipelagic in the core description (mud grain size in Fig. 3) yields a "background" sedimentation rate of ~42 cm/k.y. for the entire succession, which is consistent with measures from other Santa Monica Basin cores during the Holocene (e.g., Normark and McGann, 2004). Hemipelagic rates for the two equal-duration subdivisions are 26 and 57 cm/k.y. for the older and younger sections, respectively (Table 4).

Methods for calculating accumulation rates used for dominantly pelagic or hemipelagic sediment archives (e.g., Hebbeln et al., 2007) are unsuitable by themselves for this turbiditic succession and are therefore supplemented with analyses of recurrence interval (i.e., turbidity-current event frequency) and sedimentologic character (i.e., grain size and bed thickness). In this ponded basin-plain setting, the thickness of sand per turbidity-current event is a suitable proxy for the magnitude of an event and thus sediment delivered to the basin. The amount of sand per event (as measured in the basin plain) has increased significantly from 7 ka to present, especially in the last 2 k.y. (Fig. 8). Approximately 65% of the sand at ODP Site 1015 has been deposited over a 1.7 k.y. interval (2.17–0.48 ka), which is only 25% of the total duration of the studied succession (Fig. 8).

DISCUSSION

Relationship to Sediment-Flux History in Santa Barbara Basin

Partitioning of terrigenous sediment into Santa Monica Basin and the adjacent Santa Barbara Basin as a function of grain size (Normark et al., 1998; Piper and Normark, 2001) is an important characteristic regarding a comprehensive source-to-sink evaluation for the northern Borderland. Submarine conduits capable of delivering coarse-grained sediment to Santa Barbara Basin were abandoned during post-LGM transgression, and, as a result, Santa Barbara Basin received predominantly fine-grained terrigenous sediment in the latest Pleistocene and Holocene from muddy Santa Clara River plumes (Fleischer, 1972). During this period, Santa Monica Basin received all of the coarse-grained sediment that was delivered to deep water and some of the mud, whereas Santa Barbara Basin received much of the mud and none of the coarse-grained sediment. The total sediment accumulation rate for ODP Site 893 in Santa Barbara Basin from ca. 6.2 ka to present is ~140 cm/k.y. (Rack et al., 1995), which is 3.5 times higher than the hemipelagic rate calculated from ODP Site 1015 for the same period (42 cm/k.y.; Table 3).

The number of thin (<3 cm), gray, silty clay beds in ODP Site 893, which have been interpreted as deposits of Santa Clara River flood events, noticeably increases between 3 and 2 ka (Fig. 9; Rack and Merrill, 1995). The Santa Barbara Basin also contains a record of very recent

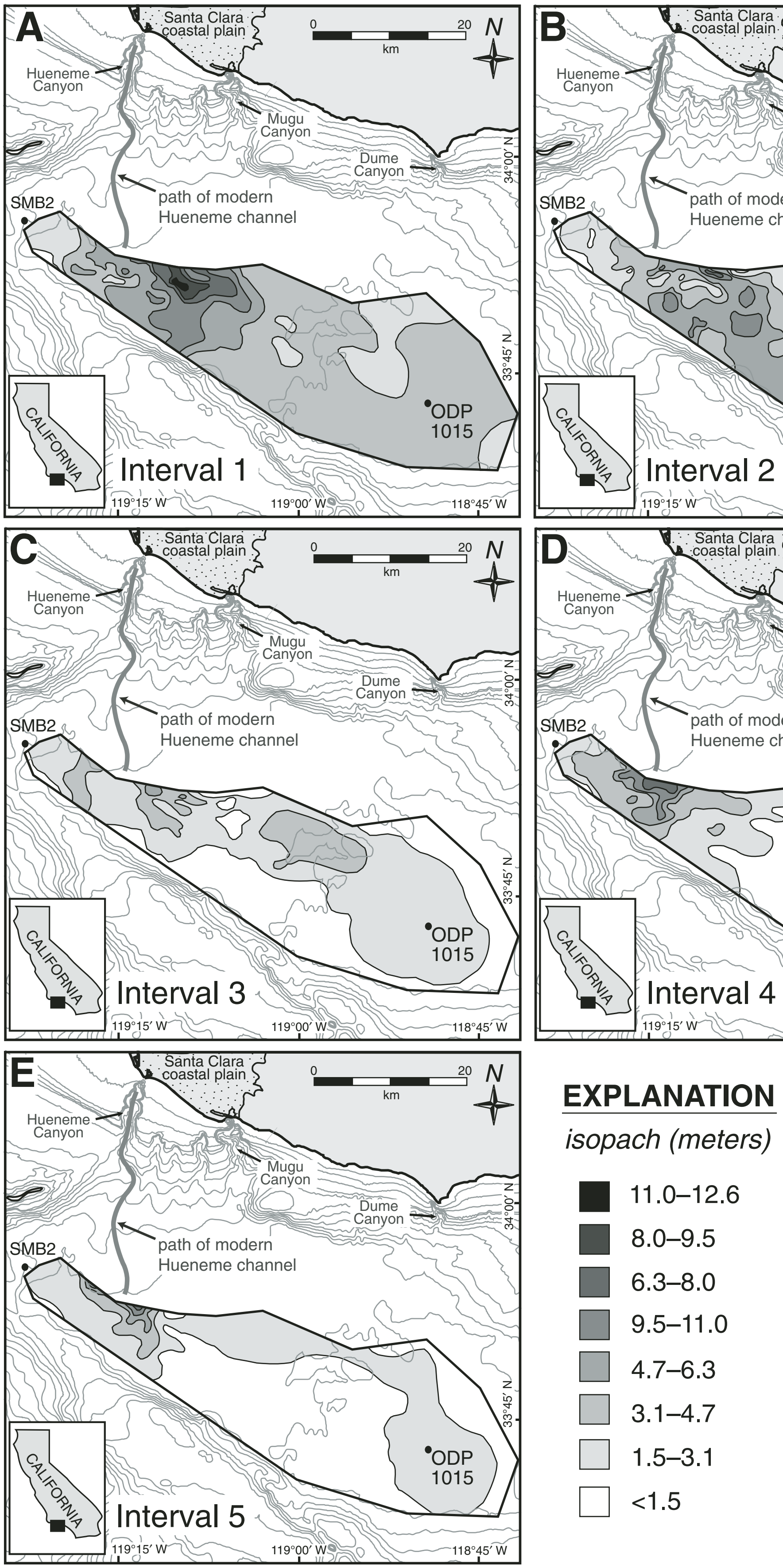

Figure 5. High-resolution isopach maps for (A) interval 1 (6.89–4.15 ka), (B) interval 2 (4.15–1.76 ka), (C) interval 3 (1.76–1.65 ka), (D) interval 4 (1.65–0.70 ka), and (E) interval 5 (0.70 ka–seafloor [present]). Contours are based on mapping of seismic-reflection data (assuming 0.79 m/ms) and have been multiplied by their area to obtain sediment volumes. Correlations are constrained by radiocarbon ages at Ocean Drilling Program (ODP) Site 1015 in basin plain and SMB2 core from Normark and McGann (2004) on the southwestern slope. See Figure 3 for description of ODP Site 1015 core, and positions of radiocarbon ages. The ODP Site 1015 core tie to seismic-reflection data is shown in Figure 4. See Figure 2 for track lines of seismic-reflection data.

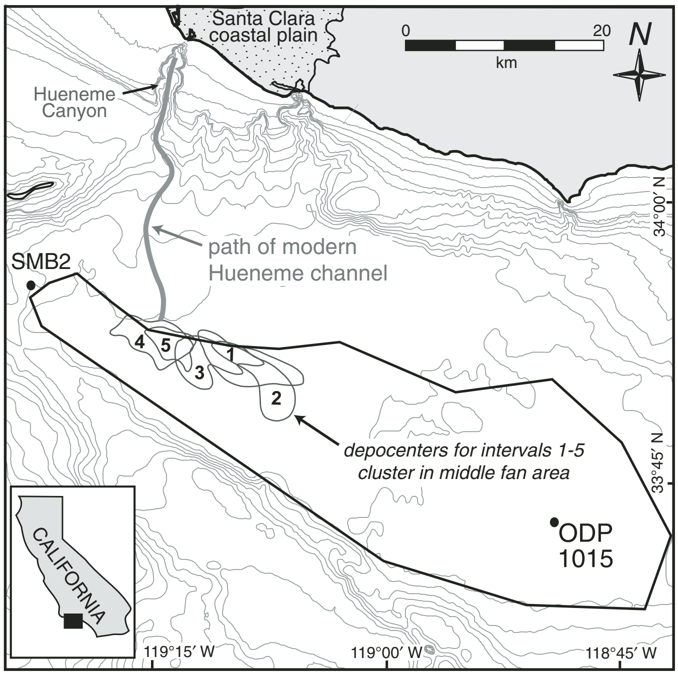

Figure 6. Map showing depocenters for intervals 1–5. Depocenters are defined as the contour that represents 80% of maximum thickness. See Figure 5 for isopach maps of each interval.

(past 100 yr) ENSO events (Lange et al., 1987), which is consistent with measurements of sediment flux of the Santa Clara River during historical times (Inman and Jenkins, 1999; Warrick and Milliman, 2003). The Holocene Santa Barbara Basin and Santa Monica Basin sediment archives are distinct with respect to some transport processes (i.e., partitioning of fine- and coarse-grained sediment); however, together, they both record an increase in Santa Clara River–derived terrigenous input in the late Holocene.

Controls on Delivery and Distribution of Terrigenous Sediment in Santa Monica Basin

Climatic Fluctuations

Climatic fluctuations that influence sediment flux for coastal southern California during the middle to late Holocene are dominated by variability of the El Niño–Southern Oscillation (ENSO) index (Inman and Jenkins, 1999; Barron et al., 2003). Historical records of the Santa Clara River show a strong correlation of increased sediment flux with increased frequency and magnitude of ENSO events (Inman and Jenkins, 1999; Warrick and Milliman, 2003; Andrews et al., 2004; Warrick et al., 2004; Warrick and Farnsworth, 2009). Approximately 90% of the twentieth-century Santa Clara River load occurred during years with a high ENSO index (Andrews et al., 2004; Warrick and Farnsworth, 2009). Moreover, higher proportions of coarse-grained sediment (i.e., sand and gravel) are associated with higher discharge rates of the Santa Clara River (Warrick and Rubin, 2007; Warrick and Farnsworth, 2009).

The ENSO proxy record from Moy et al. (2002) shows a marked increase in ENSO frequency starting ca. 3 ka (Fig. 9). The shift from colder to warmer winter sea-surface temperatures (SSTs), the latter of which are sensitive to ENSO conditions, is evident at ca. 3.2 ka from California marine records of Barron et al. (2003) (Fig. 9). In general, studies of ENSO variability indicate a relatively consistent, and weakened, ENSO ca. 8–5 ka, followed by intensified, and more variable, ENSO cycles from ca. 5 ka to present (e.g., Moy et al., 2002; Riedinger et al., 2002; Masters, 2006). The record from the adjacent Santa Barbara Basin shows that the number of Santa Clara River flood events (i.e., gray beds in ODP Site 893) increased ca. 3 ka, corroborating the interpretation that the sediment flux of the Santa Clara River increased in response to ENSO variability (Fig. 9).

Sea-Level Fluctuations

Changes of sea level are known to have significant effects on the position of coastal and nearshore depositional environments, especially over long time scales (>10 k.y.). The development and response of depositional systems tied to sea level can also have an influence on up- and downdip components of a linked source-to-sink system. The studied interval marks the transition from a transgressive (ca. 18–6 ka) to highstand (ca. 6 ka–present) state of sea level (Fig. 9; Lambeck and Chappell, 2001). Transfer of sediment from nearshore to deep-marine basins during a highstand is common in the Borderland, largely because submarine canyons are able to maintain their connection to sediment sources (Covault et al., 2007; Piper and Normark, 2001; Normark et al., 2009).

Santa Clara River Coastal Plain Sedimentation History

The development of Hueneme submarine canyon during postglacial transgression (starting ca. 18 ka), and thus its effect on sediment delivery to Santa Monica Basin, is linked with the evolution of the Santa Clara River coastal plain. The present shelf edge offshore the Santa Clara River marks the limit of the Pleistocene delta that developed during the LGM lowstand (Nardin, 1981; Dahlen et al., 1990). The Holocene Hueneme and Mugu Canyons were incised into the Pleistocene delta deposits that make up the present continental shelf and slope (Fig. 2; Nardin, 1981; Dahlen et al., 1990; Normark et al., 1998). Bathymetric maps and seismic-reflection profiles indicate that series of submarine canyons that were active in the Pleistocene are abandoned and stranded at the current shelf edge (Fig. 2; Fischer, 1972; Greene et al., 1978; Dahlen et al.,

TABLE 3. SUMMARY OF VOLUME DATA

Stratigraphic interval	Bulk volume (km^3)	Sediment volume (km^3)*	Sediment mass (tons)[†]	Duration (yr)	Sediment accumulation rate (tons/yr)	Sediment accumulation rate (km^3/k.y.)
Intervals 1–5 together	14.26	8.84	2.58×10^{10}	6900	3.74×10^6	1.28
Interval 5	1.72	1.07	3.11×10^9	700	4.44×10^6	1.53
Interval 4	2.18	1.35	3.95×10^9	950	4.16×10^6	1.42
Interval 3	2.22	1.38	4.02×10^9	110	3.65×10^7	12.55
Interval 2	3.57	2.21	6.46×10^9	2390	2.70×10^6	0.92
Interval 1	4.58	2.84	8.29×10^9	2750	3.01×10^6	1.03

*Porosity of 38% was used to convert bulk volume to sediment volume (Shipboard Scientific Party, 1997).

[†]A density of 2.65 g/cm^3 was used to convert volume to mass.

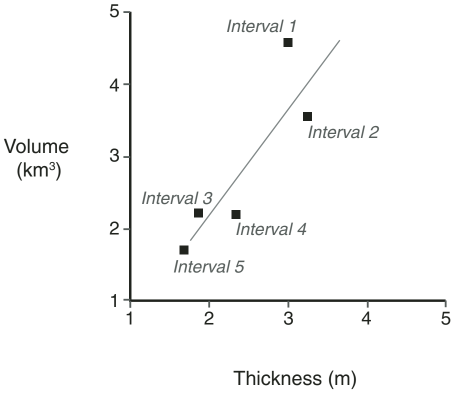

Figure 7. Comparison of mapped volumes (km^3) and thicknesses (m) as measured at Ocean Drilling Program (ODP) Site 1015 shows that, in general, the change in thickness in the basin plain corresponds to a similar change in volume on the middle-lower fan and basin plain.

TABLE 4. NEARLY EQUAL-DURATION SECTIONS OF STUDIED INTERVAL

Section*	Thickness (m)	Duration (k.y.)	Number of turbidity-current events	Recurrence interval (k.y.)	Sedimentation rate (m/k.y.)	Average sand thickness per event (m)	Hemipelagic sedimentation rate (m/k.y.)[†]
Younger	8.28	3.25	11	0.30	2.55	0.30	0.57
Older	4.16	3.65	10	0.36	1.14	0.04	0.26

*Uppermost 12.5 m of Ocean Drilling Program (ODP) Site 1015 was divided into two sections of nearly equal duration to minimize effect of measurement interval bias (Sadler, 1981). See text for further explanation.

[†] Thickness of hemipelagic intervals was determined by summing mud intervals from core description (Fig. 3).

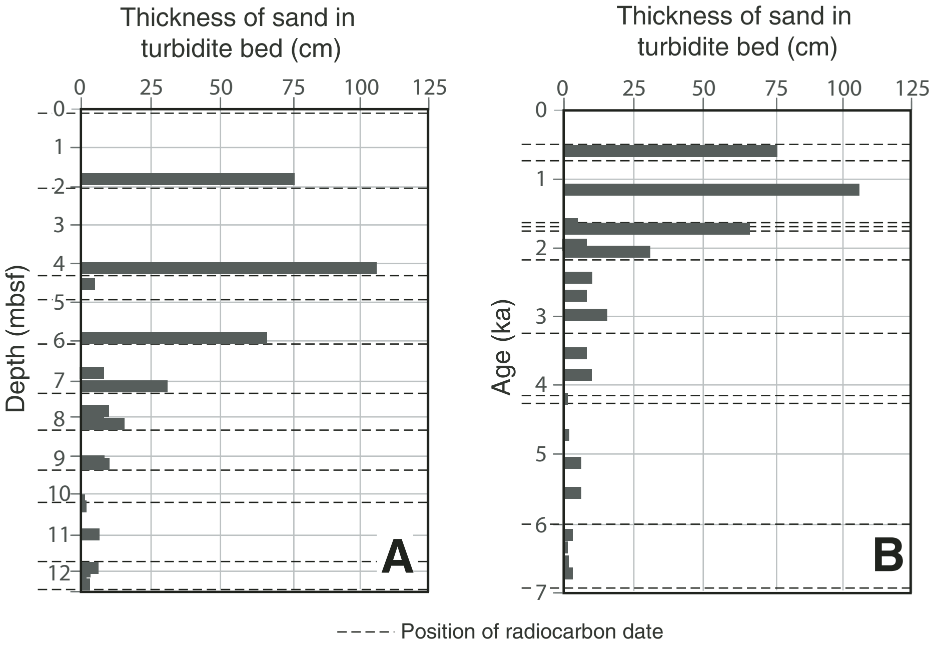

Figure 8. (A) Plot showing thickness of sand in turbidite beds against depth in core (mbsf—meters below seafloor). (B) Companion plot showing thickness of sand beds against age. Horizontal dashed lines mark positions of radiocarbon ages. See Figure 3 for full core description and Figure 2 for tie to seismic-reflection data.

1990; Normark et al., 1998, 2006; Piper et al., 1999). Hueneme and Mugu Canyons continued to deliver sediment to Santa Monica Basin during postglacial transgression because their connections to the Santa Clara River and Calleguas Creek, respectively, were maintained.

The present position of the Santa Clara River mouth is ~8 km to the northwest of the head of Hueneme Canyon (Fig. 1). There is no major submarine conduit seaward of the Santa Clara River mouth; coarse-grained sediment is incorporated into the eastward-flowing Santa Barbara littoral cell and then into Hueneme Canyon (Normark et al., 1998). Maps of the surficial geology of onshore Santa Clara River coastal plain confirm that the river mouth was directly connected to the head of Hueneme Canyon (Hitchcock et al., 2000; Clahan, 2003). Stream deposits in a series of older fluvial channels are mapped as Holocene wash deposits; the precise age of these deposits, and thus activity of the fluvial channels (at millennial scales), is uncertain (Hitchcock et al., 2000; Clahan, 2003). Given that the headward erosion of Hueneme Canyon was a function of direct fluvial input throughout most of the Holocene (Fleischer, 1972; Dahlen et al., 1990), and that the canyon head is currently positioned very close to the shoreline (<0.5 km), we interpret the timing of abandonment of the older fluvial channel to be no older than when sea level reached its current position (ca. 3 ka).

Sediment Routing in the Staging Area and Turbidity-Current Initiation Mechanisms

This study documents the overall increase in sediment flux to Santa Monica Basin during the middle to late Holocene, but not the specific initiation mechanisms of individual sediment gravity-flow events. However, the abandonment of a Santa Clara River channel leading directly into Hueneme submarine canyon, interpreted to have occurred ca. 2–3 ka, likely altered the nature of sediment input significantly. When the river mouth and canyon head were in direct connection, the potential for both river-flood–generated (i.e., hyperpycnal flows) and mouth-bar-failure–generated turbidity currents was higher (e.g., Prior and Bornhold, 1989; Prior and Bornhold, 1990; Mulder et al., 1998; Mitchell, 2005). When the river mouth moved away from the canyon head, failure of accumulated sediment (via various triggers) at the canyon head was the probable initiation mechanism for large turbidity currents. Coarse-grained sediment was transported by the Santa Barbara littoral cell to a position at the canyon head. In other words, the sediment connection type changed from dominantly direct river input to littoral cell input (Fig. 10). The change in sedimentologic character of turbidite beds at ODP Site 1015 from thinner and finer-grained (7–2.17 ka) to thicker and coarser-grained since 2.17 ka indicates that turbidity currents made it farther into the basin (Fig. 3). The maps of sediment distribution indicate that there has been no significant basinward shift of the channel-lobe transition, thereby precluding a purely autogenic interpretation of the stacking pattern (Fig. 6). The turbidity-current frequency (as recorded in the basin plain) does not appreciably change; however, the volume of sediment per turbidity-current event changes significantly (Table 4). Therefore, the turbidity currents that deposited the four prominent sand beds since 2.17 ka were comparatively more efficient (sensu Mutti, 1979; Mutti and Normark,

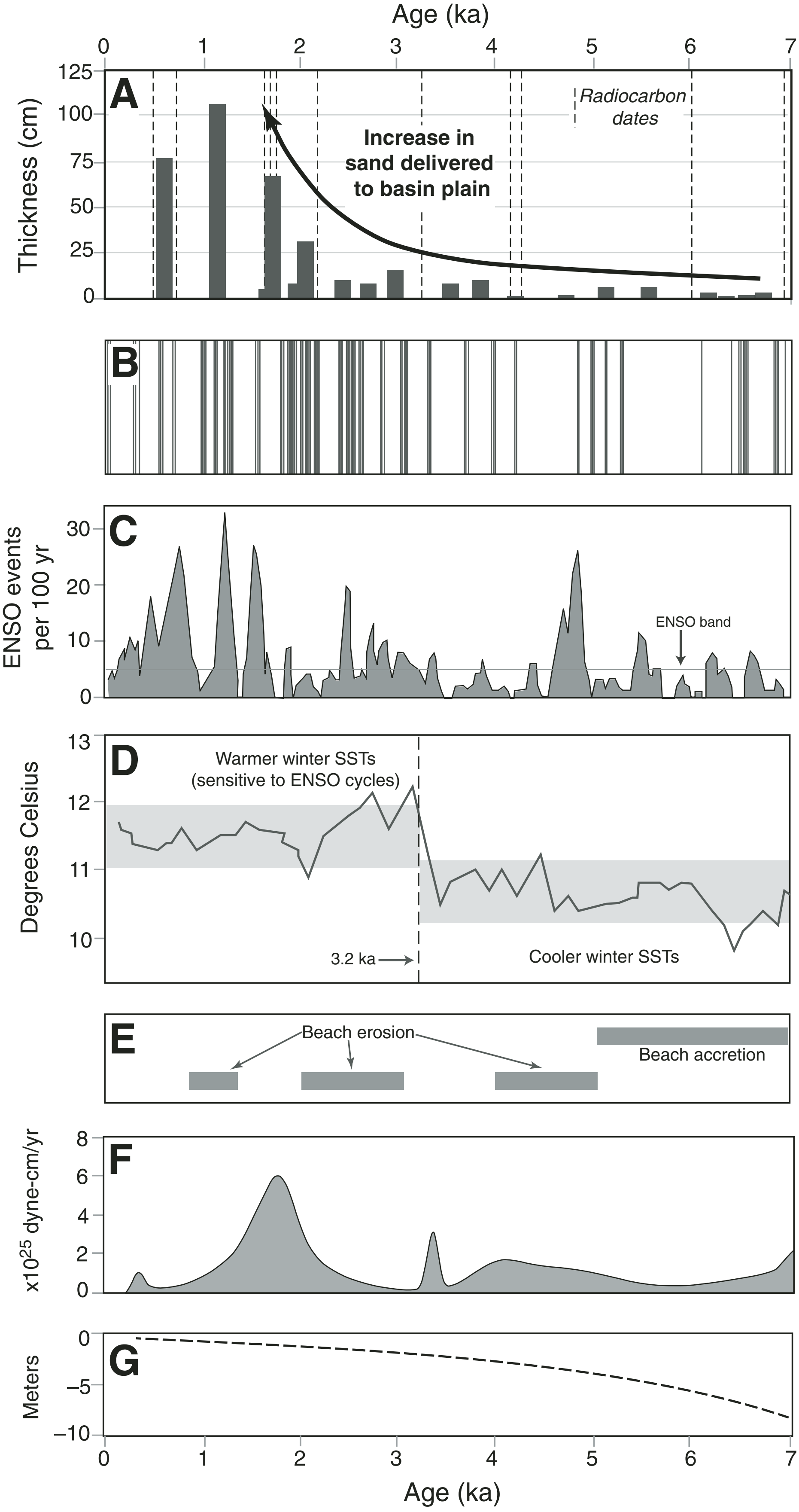

Figure 9. (A) Turbidite age and sand thickness plot showing timing and magnitude of large turbidity-current events in Santa Monica Basin plain (this study). (B) Approximate age of thin (<3 cm) flood-event beds in Ocean Drilling Program (ODP) Site 893 in adjacent Santa Barbara Basin (Rack and Merrill, 1995). (C) History of number of El Niño–Southern Oscillation (ENSO) events per century from lake sediment records in northwestern South America (Moy et al., 2002). (D) Winter sea-surface temperatures (SSTs) derived from alkenones offshore central and northern California coast. Warmer winter SSTs correspond to increased magnitude and frequency of ENSO events (Barron et al., 2003). (E) Beach accretion and erosion data from Santa Barbara littoral cell (Masters, 2006). (F) Paleoseismologic record showing probability of moment release for Los Angeles area faults (Dolan et al., 2007). (G) Sea-level curve (Lambeck and Chappell, 2001).

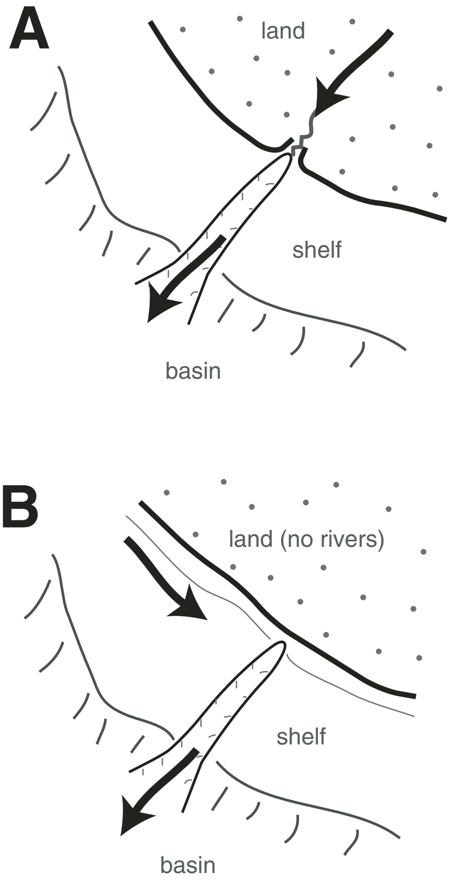

Figure 10. Simplified schematic diagrams comparing different staging area "connection types." (A) Conditions from 7 ka to ca. 2 ka in which Santa Clara River fed directly into Hueneme submarine canyon. Surficial maps on the Oxnard Plain confirm presence of Holocene stream deposits leading to canyon head (Clahan, 2003). (B) At ca. 2 ka, the Santa Clara River switched course to its present position ~8 km to the northwest of the head of Hueneme Canyon. Hueneme Canyon has thus been fed by littoral cell input from 2 ka to present.

1987) at carrying coarse-grained sediment to the basin plain. The effect that the better-sorted littoral-fed sand as compared to less-well-sorted river-fed sand had on initial conditions of turbidity currents is unknown but potentially significant regarding down-system flow evolution.

Masters (2006) documented the history of sand accumulation within the Santa Barbara littoral cell and determined the period of most active beach accretion to be 6–5 ka, in accord with the slowing of sea-level rise (Fig. 9). The increased ENSO frequency and magnitude since 5 ka (Moy et al., 2002) led to erosion of beaches as a result of increased storm and wave action along the coast (Masters, 2006). Increased erosion of beaches led to increased transport along the Santa Barbara littoral cell, which likely led to increased input into Hueneme Canyon and thus delivery to Santa Monica Basin.

Tectonic Setting and Activity

The relatively high sediment yield of the modern Santa Clara River (second only to the Eel River on the west coast of the United States) is a consequence of the geology of the Western Transverse Ranges. The bedrock of the Santa Clara River watershed is composed of weak and easily eroded Cenozoic sedimentary rocks (Scott and Williams, 1978; Inman and Jenkins, 1999; Warrick and Farnsworth, 2009). The variability of rates of tectonic movement at millennial scales for the Transverse Ranges and northern Borderland is not well constrained. Uplift rates estimated for the Santa Monica Mountains (0.1–0.9 m/k.y.) confirm that the region's high relief was maintained during the Holocene (e.g., Meigs et al., 1999; Lajoie et al., 1979). Uplift rates for parts of the Western Transverse Ranges near the towns of Santa Barbara and Ventura (Fig. 1) are as high as 10 m/k.y. (Yerkes and Lee, 1987). Rates determined from a longer-term record along a left-lateral fault that marks the northern boundary of Santa Monica Basin and structural front of the Western Transverse Ranges have been estimated to be ~1.25 m/k.y. (Sorlien et al., 2006). Movement along this fault likely had a direct effect on timing of large failure-induced turbidity currents. A recent paleoseismologic compilation by Dolan et al. (2007) for Holocene earthquake activity in southern California shows temporal clustering of cumulative seismic-moment release data for Los Angeles–area faults at 12–10 ka, 8–7 ka, and 2–1.5 ka. The most recent seismic activity coincides with the increase in sand delivery to the basin plain, suggesting earthquakes could have been the trigger for large-magnitude failures of littoral-fed sand accumulations into Hueneme Canyon (Fig. 9).

Turbidite System Evolution Recorded in a Ponded Basin Plain Succession

Information from ODP Site 1015 affords the opportunity to evaluate a basin-plain stratigraphic succession and its relationship to overall turbidite system evolution. Although only the largest turbidity-current events reach the flat basin plain (35 km from the mouth of Hueneme submarine channel; 65 km from the head of Hueneme submarine canyon), it is the most complete record of sedimentation history available at any single location for Santa Monica Basin. Stratigraphic successions in proximal areas of the fan and in the canyon are more complex as a result of nonuniform deposition, bypass, or erosion (Normark et al., 1998; Piper et al., 1999). The acoustic character of the high-resolution seismic-reflection data (Fig. 4) and the sedimentologic characteristics of the ODP Site 1015 core (Fig. 3) suggest that erosion at the base of turbidite beds is minor in this basin-plain position. Additionally, it is important to reiterate that Santa Monica Basin is a "closed" basin; flows are trapped and do not spill into adjacent basins (Normark et al., 2006, 2009).

The section of core analyzed in this study shows an overall upward–bed thickening and upward-coarsening trend (Fig. 3). Similar patterns observed in ancient turbidite successions (although typically in thicker successions) have been interpreted as the record of submarine fan progradation (e.g., Walker, 1978). The isopach maps show that the depocenters for each of the five stratigraphic intervals are all in the middle fan area (Fig. 5). The orientations of the depocenter shifts are primarily in a lateral direction, reflecting compensational stacking of channel-mouth lobe deposits and continued construction of the middle fan (Fig. 6). The two uppermost mapped intervals correspond to the two uppermost thick beds in the basin plain (Fig. 3), and, although their main depocenters are positioned at the channel-mouth area, their mapped distribution also shows a subtle pattern of thinning across the lower fan area compared to the more distal basin plain (Figs. 5 and 6). We interpret this pattern to reflect basin-plain ponding of these comparably larger turbidity currents. Although the flows deposited some sediment at the channel-lobe transition, they were of sufficient magnitude to continue down system, depositing a relatively thin veneer on the lower fan, and then depositing the remainder of the sediment load on the flat basin plain. An understanding of sediment distribution, and thus the ability to predict resultant stratigraphic architecture in ponded systems, has important implications for the exploration and management of hydrocarbon reservoirs in ponded basins (e.g., Prather et al., 1998; Lonergan and Cartwright, 1999; Sinclair, 2000; Adeogba et al., 2005).

CONCLUSIONS

New radiocarbon dates and resultant temporal constraint on sedimentation events in Santa Monica Basin provide an opportunity to evaluate factors that control coarse-grained terrigenous sediment flux to a deep-marine basin. Within the context of conventional stratigraphic studies, which typically do not have such high-resolution temporal constraint, the depositional history documented in this study addresses high-frequency controls and patterns. Six new radiocarbon dates are integrated with five previously published, but recalibrated, dates from a 12.5-m-thick turbidite section from ODP Site 1015 in Santa Monica Basin, offshore California. This borehole is tied to high-resolution seismic-reflection profiles that cover an 1100 km^2 area of the middle and lower Hueneme submarine fan and most of the basin plain.

The depositional history from 7 ka to present indicates that the recurrence interval for large turbidity-current events is relatively constant (300–360 yr), but the volume of coarse-grained sediment (i.e., silt and sand) deposited on the fan and in the basin plain has increased by a factor of 2 over this period. Moreover, the amount of sand per turbidity-current event on the basin plain during the same interval has increased by a factor of 7. Maps of sediment distribution derived from correlation of seismic-reflection profiles indicate that this trend cannot be attributed exclusively to autogenic processes (e.g., lobe progradation). The observed variability in sediment accumulation rates is thus largely controlled by interacting allogenic factors, including: (1) increased sediment discharge of Santa Clara River as a result of increased magnitude and frequency of ENSO events from ca. 2 ka to present, (2) an apparent change in routing of coarse-grained sediment within the staging area at ca. 3 ka (i.e., from direct river input to indirect, littoral cell input into Hueneme submarine canyon), and (3) decreasing rates of sea-level rise (i.e., rate of rise slows considerably by ca. 3 ka). We infer that the overriding control is the climatic shift at ca. 2–3 ka.

These results highlight the importance of understanding the interactions of fluctuating climate and sediment routing pathways. In this case, increased ENSO activity increased the volume of sediment available for transport to Santa Monica Basin in two ways: (1) increased precipitation led to higher sediment flux of the Santa Clara River; and (2) increased storm and wave activity led to beach erosion and increased sediment transport in the Santa Barbara littoral cell. The basinal stratigraphic section is thus a signal of changing sediment routing in the staging area superimposed on the more fundamental control of changing climatic conditions.

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