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Late Quaternary Deposition in the Inner Basins of the California Continental Borderland—
Part A. Santa Monica

Scientific Investigations Report 2004–5183

U.S. Department of the Interior
U.S. Geological Survey

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By William R. Normark and Mary McGann

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Abstract

Radiocarbon dating of sediment core samples from Santa Monica Basin document Holocene (younger than approximately 11 ka) landslides and fault offsets along the basin margin. The new dates include 17 from six piston cores on the continental slope and 11 from Ocean Drilling Program Site 1015 on the basin floor. The dates, which are based on data from pelagic and benthic foraminifera in addition to several dates from mollusk shells, are used to provide chronostratigraphic control for a previously determined basin-wide seismic stratigraphy. The geologic setting at the core sites and a sediment log for each core are shown. In addition, each sediment log is accompanied by a color core photograph as well as P-wave velocity and gamma-ray density profiles. The primary purpose of the report is to make the radiocarbon dates available for other studies in the Santa Monica Basin. A comparison of sediment accumulation rates between the late Pleistocene and Holocene provides insight to the effects of sea-level change on sediment input to the basin. In addition, the results can be used to evaluate the effectiveness of wire-line piston coring in providing age control for earthquake hazard and sedimentologic studies.

Introduction

In recent years, the Santa Monica Bay has been the focus of intensive sampling programs in support of studies that dealt with sediment sources, sediment distribution patterns, and transport processes, particularly in regard to pollutant issues (see for example, Lee and Weisberg, 2003). Beginning in 1998, a series of sediment coring efforts beginning in the Santa Monica Basin focused on the deeper water areas of the inner basins of the California Borderland. The primary intent of the deeper water work was to determine sediment accumulation rates along the basin margins in order to provide age control for active faults and recent submarine landslides. Radiocarbon dating of U.S. Geological Survey (USGS) piston cores was combined with dating of the core recovered at ODP Site 1015 (Shipboard Scientific Party, 1997). The sedimentation rate data show limited effects of sea level change on sediment supply to the basin, compared to the effect on sedimentation rates on the adjacent shelf and slope of Santa Monica Bay reported by and Lee (2004).

Earthquake hazard studies

The focus of the southern California earthquake-hazard task is to identify the nature of threats from landslides, earthquakes, and tsunamis in the offshore southern California coastal region. To meet this objective, it is necessary to determine the style and timing of active (Holocene) deformation within the basins and slope areas adjacent to the highly populated urban corridor from Santa Barbara to San Diego. High-resolution seismic-refection profiles are used to determine the sites for sediment-core samples that can be used to date fault offsets, active folding, and submarine landslides. This report is the first in a series that will describe the geological setting of the sample localities, the sedimentological and geophysical log properties of the core samples, the radiocarbon ages of the sediment recovered, and the resulting implications for dating of tectonic activity.

The study area for this report is the Santa Monica Basin west of Los Angeles (fig. 1). This northwest-southeast trending basin, which has a maximum water depth approaching 1,000 m, subsided during the Pliocene and Quaternary in a predominantly strike-slip tectonic regime (Crouch and Suppe, 1993; Sorlien and others, 2003). Except to the southeast, where the Santa Monica Basin is separated from San Pedro Basin by bedrock of the Redondo Knoll, the basin is bounded by a complex arrangement of strike slip, reverse, and buried thrust faults (see for example, Nardin and Henyey, 1978; Sorlien, 1999, Dolan and others, 2000; Sorlien and others, 2003; Fisher and others, 2003). During the latest Quaternary, the Santa Monica Basin has been filling with sediment at accumulation rates as much as 3 m/ka (Shipboard Scientific Party, 1997). Dume and Santa Monica canyons provide modest sediment to low-relief submarine fans at the base of the slope, but the dominant source of sediment is the Hueneme Canyon at the western end of the basin (fig. 1; Normark and others, 1998; Piper and others, 1999; Piper and Normark, 2001). Hueneme Canyon cuts across the shelf and receives much of the coarse sediment delivered to the coast from the Santa Clara River, from which hyperpycnal flows deliver sediment directly to the canyon and adjacent basin slope (Warrick and Milliman, 2003).

Normark and Piper (1998) provided a preliminary assessment of Holocene deformation along the margins of the Santa Monica Basin. High-resolution seismic-reflection data collected by the Geological Survey of Canada (GSC; see

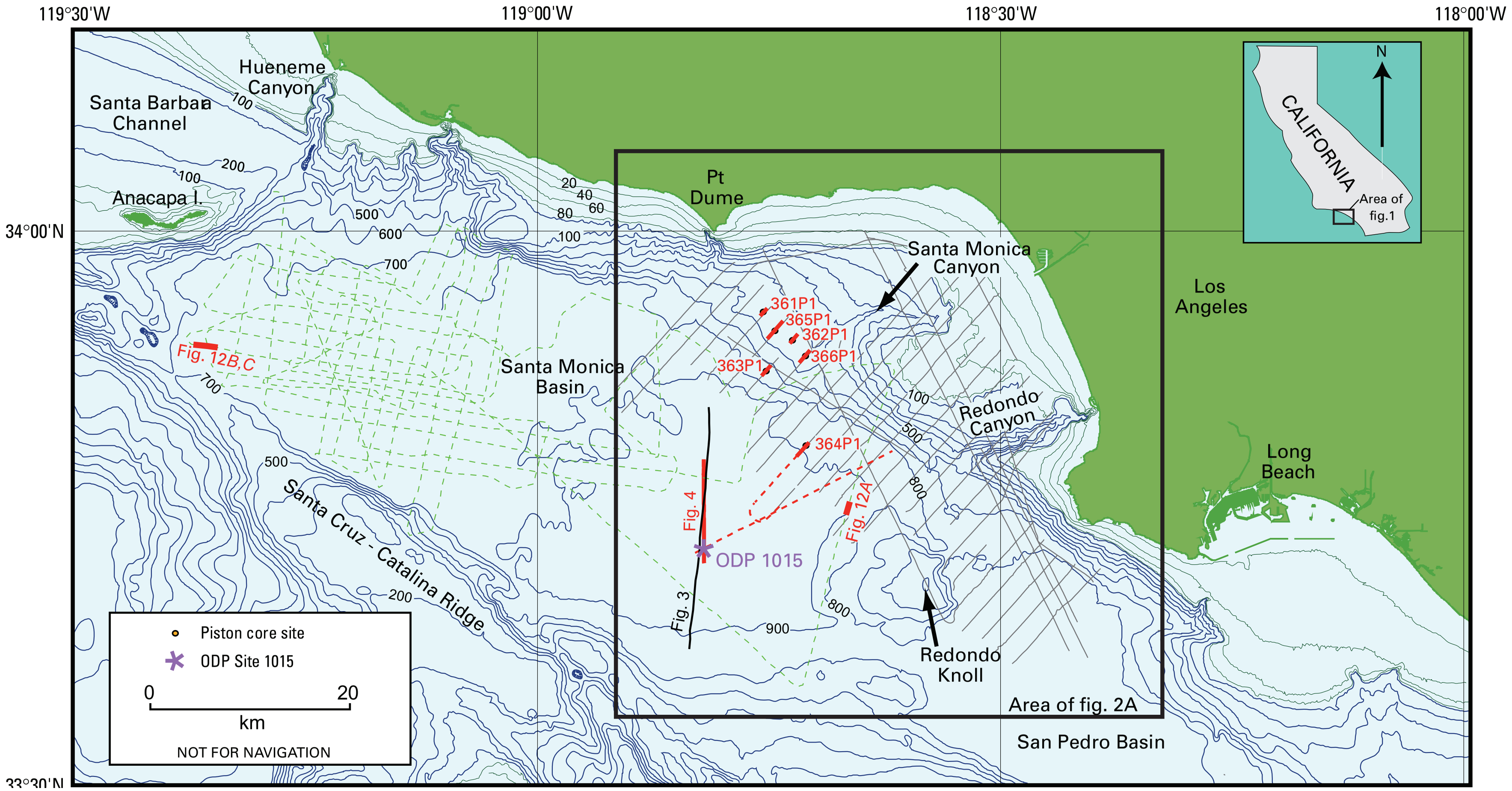


Figure 1. Bathymetric map of Santa Monica Basin showing position of cores used in this study (ODP Site 1015 and piston cores 361P1 through 366P1). Thin green, dashed lines show tracklines for Geological Survey of Canada (GSC) cruise 91-062. Thin dark gray lines show tracklines for deep-tow boomer profiles collected during U.S. Geological Survey cruises A-1-98-SC and O-1-99-SC in support of earthquake hazard assessment for offshore southern California. Locations of the seismic-reflection profiles in the vicinity of ODP Site 1015 presented in figures 3 and 4 are shown as heavy solid lines in black and red, respectively. Locations of deep-tow boomer lines used to correlate the high-resolution stratigraphic framework (Normark and others, 1998; Piper and others, 1999) with ODP 1015 and piston-core site 364P1 are shown as thin, red dashed lines. Thick red lines through the piston core sites give length of boomer profiles illustrated in figures 6 through 11. Thick red lines near northwest and southeast ends of the basin show seismic-reflection profiles of figure 12. Rectangle with thick lines shows location of figure 2*A*. Bathymetric contours in meters with 20-m-interval on shelf and 100-m-interval for deeper water (adapted from NOAA, 1998).

tracklines in fig. 1) were interpreted using the depth to the Pleistocene-Holocene boundary from the initial results from Ocean Drilling Program (ODP) Site1015 (Shipboard Scientific Party, 1997). Preliminary results on the timing and recurrence of deformation in Santa Monica Basin showed that during the last 5 ka the western end of the basin is actively deforming with multiple deformational events (folding, tilting, fault offsets). Within the last 10 ka, large submarine slides have occurred, primarily south and west of Santa Monica Bay. During the last 2 ka, the northeast margin of the basin has many faults that offset the seafloor and that have been active (Normark and Piper, 1998).

The main effort of the ongoing evaluation of seismic hazard in Santa Monica Basin has been to map active structures that lie within 40 to 50 km of the shore (see USGS tracklines in fig. 1). Fisher and others (2003) demonstrated that the northeastern margin of the basin shows different degrees of deformation north and south of Santa Monica Canyon (fig. 2*A*). Northwest of this canyon, two shallow anticlines on the lower slope extend toward Point Dume and are cored by faults showing reverse or thrust separation. Southeast of Santa Monica Canyon, the lower-slope sediment is deformed by a complex arrangement of strike-slip, normal, and reverse faults along the San Pedro Escarpment that locally form flower structures (Normark and Piper, 1998; Fisher and others, 2003). These faults merge downward with the San Pedro Basin Fault Zone (fig. 2*A*), which is nearly vertical and strike-slip (Fisher and others, 2003).

Sediment accumulation rates

The high-resolution seismic-reflection data from the GSC provided a basis for establishing a detailed stratigraphic framework for sediment of late Quaternary age in the deep Santa Monica Basin (Normark and others, 1998; Piper and others, 1999; Piper and Normark, 2001). These studies identified about 15 key reflectors, many of which can be recognized across the basin floor and lower basin slopes. Some of these reflectors are shown in figures 3 and 4 where they have been further mapped using other reflection profiles collected by the USGS during 1998 (fig. 1). The GSC data did not directly intersect ODP Site 1015 (fig. 1), but the USGS data collected in 1998 did cross the drill site. Thus, the key reflectors can now be correlated with confidence to Site 1015 (figs. 4 and 5; Shipboard Scientific Party, 1997).

Site 1015 was not studied in detail for the ODP Scientific Results volume for Leg 167 and, to date, only a few unpublished radiocarbon ages have been available to evaluate deformation in Santa Monica Basin. The unpublished dates confirmed the shipboard evaluation that the Holocene deposits are nearly 30 meters thick, which is much greater than previous estimates (Shipboard Scientific Party, 1997). The Santa Monica Basin is a closed basin and makes an ideal subject for a source-to-sink evaluation of the effects of sea level on sediment supply to the deep basin floor. In addition, deep-tow boomer data have been used to show that the uppermost key reflectors can be traced from ODP Site 1015 to about 40 m above the basin floor. This suggests that turbidity currents from the Hueneme Canyon are thick enough to deposit sediment well above the basin floor (Piper and others, 2003).

To make further use of the ODP core data for both stratigraphic studies and seismic hazard evaluation, this report documents a comprehensive suite of radiocarbon ages for sediment from cores in Santa Monica Basin that can be used to refine initial efforts to determine the deformation history within the basin (see for example, Normark and Piper, 1998; Fisher and others, 2003). This study is based on data from ODP Site 1015 in addition to site-specific piston cores along the basin margin (table 1 and fig. 2*B*). Chronostratigraphic control for the basin-wide, high-resolution seismic stratigraphy developed for Santa Monica Basin can be used to date faulting and mass-wasted deposits within the basin floor and base-of-slope areas. Short piston cores from the northeastern flank of the basin were intended to provide age control for folding and faulting on the mid-slope area. The dated sediment cores are also used to evaluate sedimentation rates during the change from glacial sea-level lowstand to the present highstand.

Methods

The Santa Monica Basin receives sediment from at least four submarine canyons that are fed directly from rivers or from sand being transported in the littoral zone (fig. 1; Normark and others, 1998). For this reason, deposits in the basin are relatively sand rich (see for example, fig. 5). To develop a fine-scale seismic stratigraphy and to image active faults that offset the sea floor or strata close to the sea floor, a deep-tow boomer system was chosen to obtain the necessary vertical resolution of bedding and yet still be capable of imaging sandy deposits that are tens of meters thick. We used boomer reflection profiles to select specific core sites adjacent to fault and fold structures and then used microfossil carbonate tests for radiocarbon dating to date recent displacements.

Deep-tow boomer system

The high-resolution Huntec DTS boomer system is well suited for reflection profiling studies in basins of the California Borderland. The DTS boomer source is towed between 50 m and 160 m below the sea surface (depending upon the water depth) and can image the upper few tens of milliseconds of strata with a resolution of better than 0.5 ms (0.4 m). Power output is 350 Joules, with a firing rate that is dependent on water depth, ranging from 0.75 sec to 1.25 sec with the longer interval over the deeper water parts of the basin. For the profiles obtained in support of the Santa Monica Basin study, the receiver was a 5-m-long Benthos 10-element hydrophone array towed from the same fish that houses the boomer source.

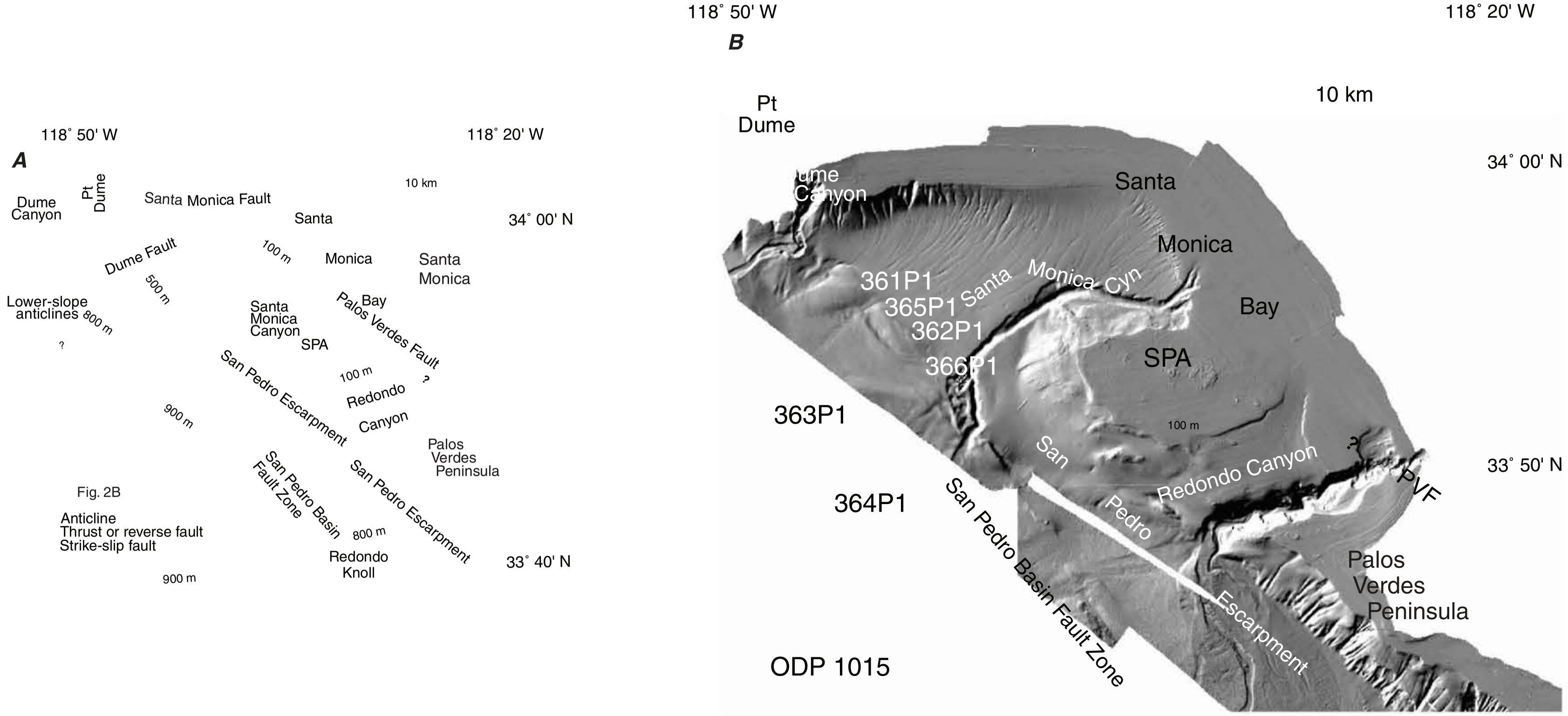


Figure 2. *A*, Summary of primary structural features (shown in black) along the northeastern margin of Santa Monica Basin as established by Fisher and others (2003). Features shown in red are schematic representation of other faults in the area (see references for figure 1 in Fisher and others, 2003). The extension of the Palos Verdes Fault (PVF) remains conjectural north of Redondo Canyon and is shown as a dashed red line. SPA is shelf projection anticlinorium. See figure 1 for location. *B*, Shaded-relief map of the shelf and basin slope east of Santa Monica Basin based on multibeam bathymetric data; view is from directly overhead with illumination from the northwest (Gardner and Dartnell, 2002). The fault and fold patterns are the same as for figure 2*A*. Piston core locations are shown together with tracklines for deep-tow reflection-profile segments of figures 6 thorugh 11 (see figure 1 for explanation).

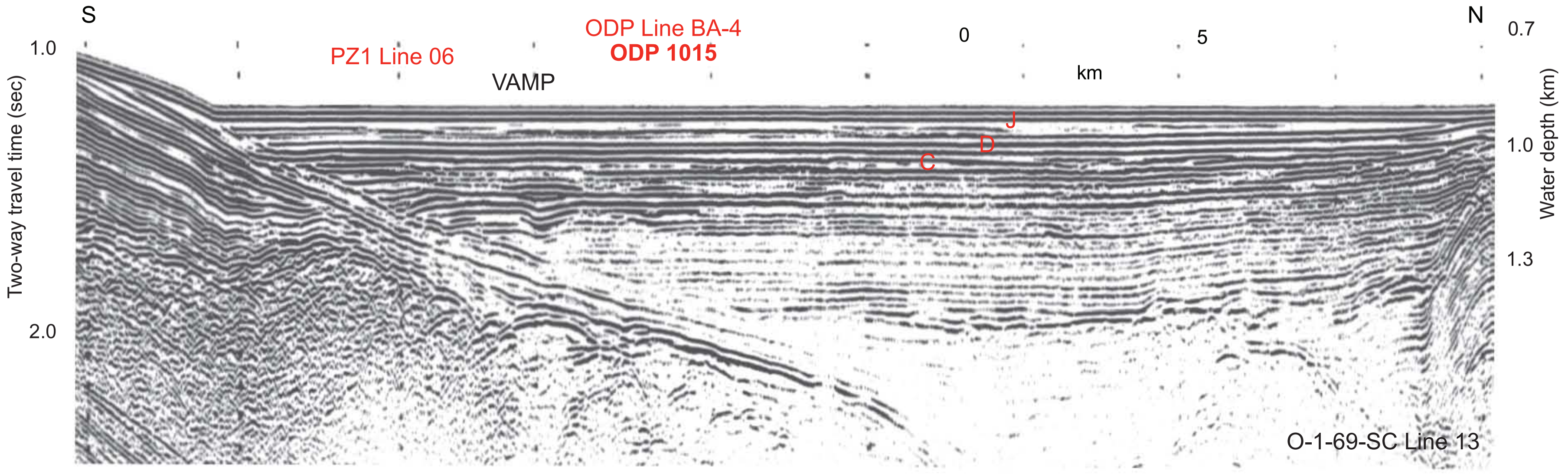
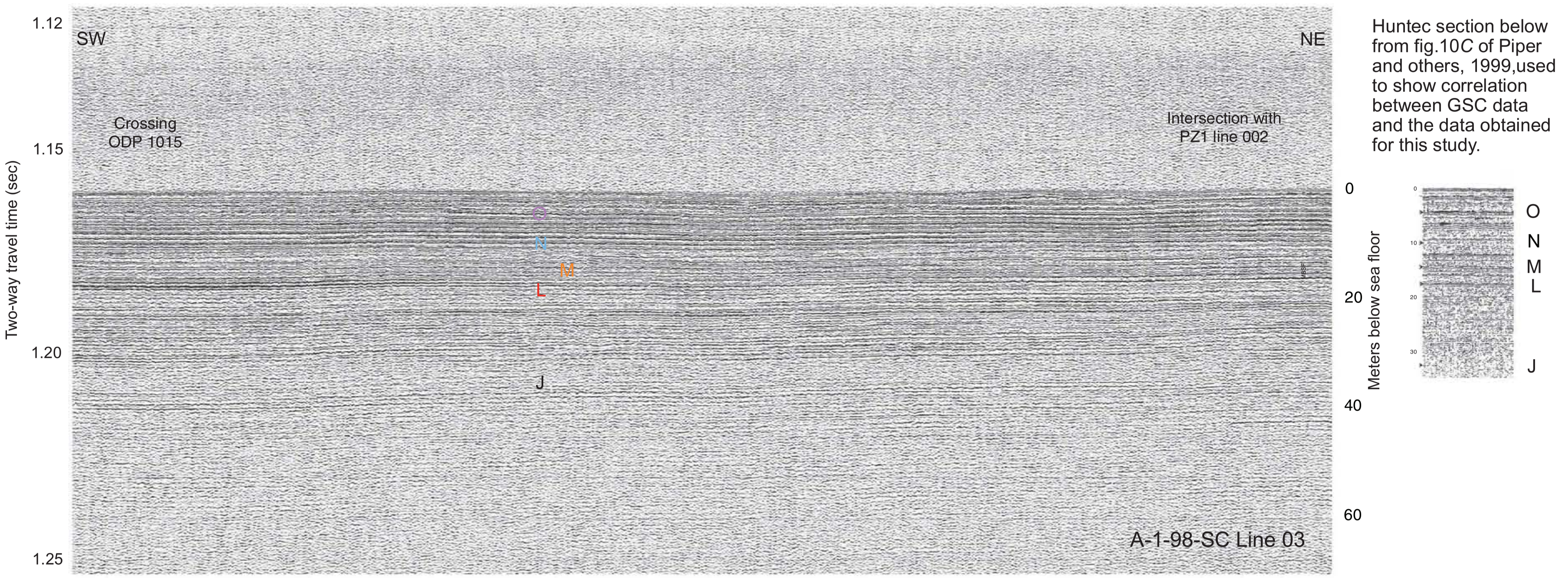


Figure 3. Seismic-reflection profile showing basin-floor stratigraphy of Santa Monica Basin sediment at ODP Site 1015. Line 13 from U.S. Geological Survey cruise O-1-69-SC. Key basin-wide stratigraphic reflectors C, D, and J are shown in this profile, which was obtained with a single-channel sparker sound source; refer to figure 4 for reflectors between J and the seafloor and see text for explanation. Profile location is shown in figure 1. This profile shows evidence for gas accumulation in the sediment below about 0.25 sec two-way travel time, which is just a few tens of meters deeper than the bottom of ODP Hole 1015A at 149.5 mbsf; see, for example, high-amplitude (bright) reflections locally with a Velocity-AMPlitude (vamp) -like structure south of the ODP drill site (see Scholl and Cooper, 1978).



Huntec section below from fig.10*C* of Piper and others, 1999,used to show correlation between GSC data and the data obtained for this study.

Figure 4. High-resolution deep-tow boomer profile that passes through ODP Site 1015 and intersects Line 2 from Geological Survey of Canada (GSC) cruise 91-062. See figure 1 for location. Reflectors O to J are regional reflectors that can be correlated throughout much of the Santa Monica Basin using the GSC survey of the western end of the basin (Piper and others, 1999) and the U.S. Geological Survey data farther east (see fig. 1).

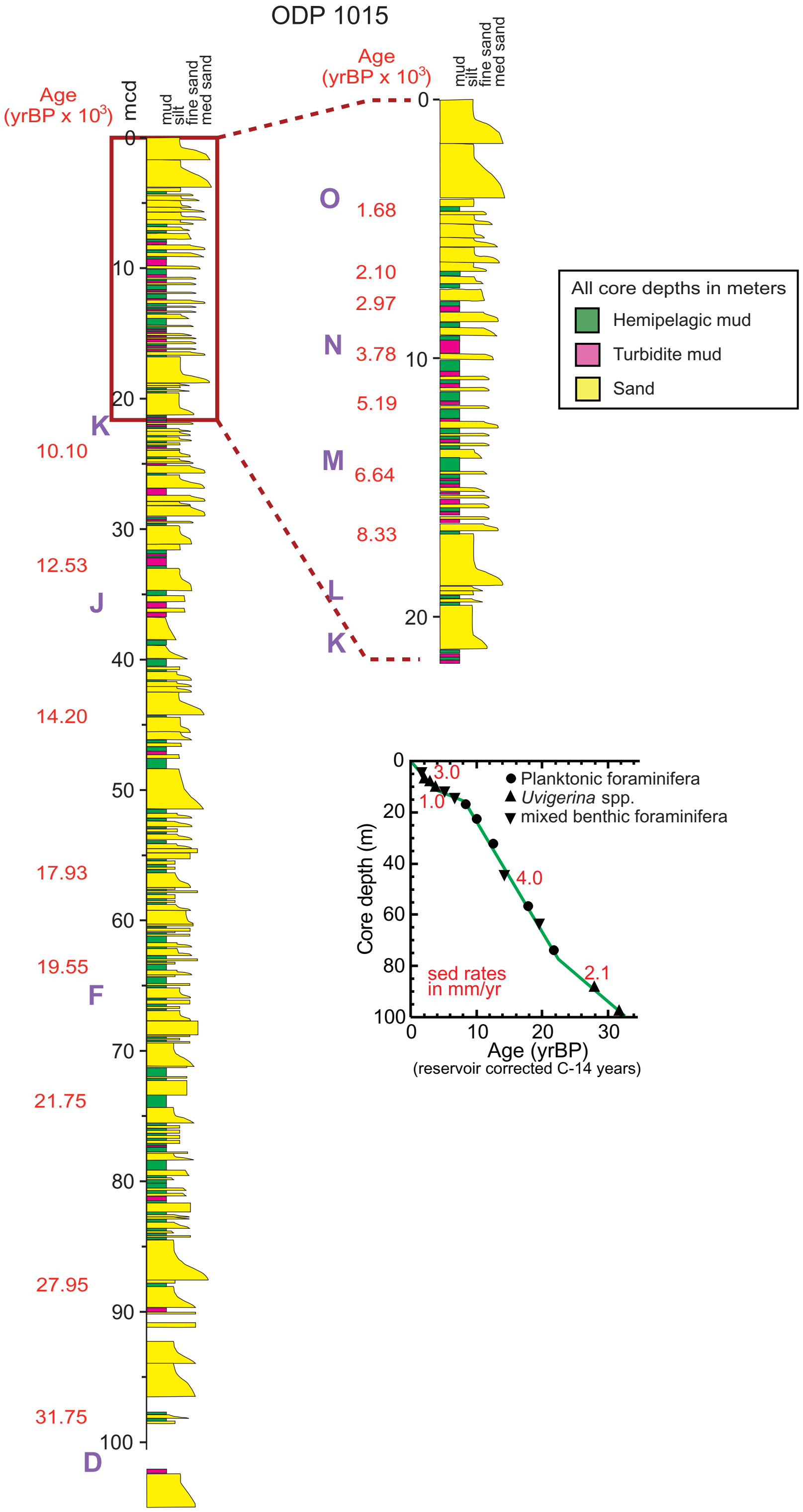


Figure 5. Graphical sediment log for ODP Site 1015 constructed from the Visual Core Descriptions (VCDs) obtained from the Ocean Drilling Program archive at Texas A&M University. The log is constructed combining the VCDs from Holes 1015A and 1015B in order to avoid disturbed sections wherever possible; thus, the vertical scale (mcd = meters core depth) reflects the combined logs. Radiocarbon dates are shown in red to the left of the sediment logs. The upper 20 m of the log is expanded (at the right) to better illustrate the relation between the radiocarbon dates and the late Holocene interval of key reflector stratigraphy. The graph at lower right shows the sediment accumulation rate in mm/yr. Location of Site 1015 in figures 1 and 2*B*.

Table 1. Radiocarbon ages from piston cores and ODP 1015 from Santa Monica Basin.

NOSAMS Accession Number	**Core, section, depth**	**Meters below sea floor (mbsf)**	**Description of dated material**	**d13C**	**^{14}C Age (yr B.P.)**	**Reservoir Age (yr)[1]**	**Corrected Age (yr B.P.)[1]**	**Calendar Age (yr B.P.)[2]**
OS-40035	A2-98-SC 361P1, sec. 1, 40-44 cm	0.40-0.44	*Gyroidina altiforms* (benthic)	-1.01	14,800±75	1,750	13,050±75	15,580±75
OS-36191	A2-98-SC 361P1, sec. 2, 36-37 cm	0.80-0.81	Mollusk	0.76	15,150±70	1,750	13,400±70	15,990±70
OS-40036	A2-98-SC 361P1, sec. 2, 75-77 cm	1.19-1.21	*Cibicides* sp. (benthic)	-0.41	17,950±95	1,750	16,200±95	19,210±95
OS-40037	A2-98-SC 361P1, sec. 2, 140-142 cm	1.84-1.86	*Cibicides* sp. (benthic)	-0.39	19,150±110	1,750	17,400±110	20,590±110
OS-40038	A2-98-SC 362P1, sec. 2, 80-82 cm	1.77-1.79	*Uvigerina* spp. (benthic)	-1.41	13,050±55	1,750	11,300±55	13,160±55
OS-39100	A2-98-SC 362P1, sec. 2, 133-135 cm	2.30-2.32	Mixed benthics	-0.98	13,000±65	1,750	11,250±65	13,150±65
OS-40039	A2-98-SC 363P1, sec. 2, 60-62 cm	1.12-1.14	*Uvigerina* spp. (benthic)	-1.23	13,650±65	1,750	11,900±65	13,820±65
OS-40066	A2-98-SC 363P1, sec. 3, 104-106 cm	3.05-3.07	Mixed benthics	-1.75	25,400±210	1,750	23,650±210	
OS-40067	A2-98-SC 363P1, sec. 4, 30-32 cm	3.65-3.67	*Uvigerina peregrina* (benthic)	-1.09	28,200±280	1,750	26,450±280	
OS-35616	A2-99-SC 363P1, sec 4, 123-125 cm	4.58-4.60	Mixed planktics	-1.82	29,200±150	1,100	28,100±150	
OS-40068	A2-98-SC 364P1, sec 1, 105-107 cm	1.05-1.07	*Uvigerina* sp. (benthic)	-0.37	4,640±35	1,750	2,890±35	3,136±35
OS-40069	A2-98-SC 364P1, sec. 3 , 28-30 cm	3.04-3.06	Mixed benthics	-1.8	9,840±55	1,750	8,090±55	8,960±55
OS-35615	A2-98-SC-364P1, sec 3, 143-145 cm	4.19-4.21	*Neogloboquadrina pachyderma*	0.12	10,600±75	800	9,800±75	11,130±75
OS-40070	A2-98-SC 365P1, sec. 2, 80-82 cm	1.39-1.41	*Uvigerina* spp. (benthic)	-3.09	> 52,000			
OS-40071	A2-98-SC 365P1, sec. 2, 100-102 cm	1.59-1.61	*Uvigerina peregrina* (benthic)	-0.8	Too old to date			
OS-39101	A2-98-SC 365P1, sec. 2, 140-142 cm	1.99-2.01	Mixed benthics	-2.38	> 54,000			
OS-40072	A2-98-SC 366P1, sec. 1, 20-22 cm	0.20-0.22	Mixed benthics	-1.01	7,990±40	1,750	6,240±40	7,182±40

Table 1. Radiocarbon ages from piston cores and ODP 1015 from Santa Monica Basin.—Continued

NOSAMS Accession Number	Core, section, depth	Meters below sea floor (mcd)	Description of dated material	d13C	^{14}C Age (yr B.P.)	Reservoir Age (yr)[1]	Corrected Age (yr B.P.)[1]	Calendar Age (yr B.P.)[2]
OS-35811	ODP 1015B, 002H 02W, 55-57 cm	4.35	Mixed benthics		3,430±45	1,750	1,680±45	1,664±45
OS-35835	ODP 1015B, 002H 03W, 144-146 cm	6.74	*Uvigerina* sp.		3,850±40	1,750	2,100±40	2,143±40
OS-35836	ODP 1015B, 002H 04W, 101-103 cm	7.81	*Uvigerina* sp.		4,720±30	1,750	2,970±30	3,238±30
OS-35837	ODP 1015B, 002H 06W, 12-14 cm	9.92	*Uvigerina* sp.		5,530±35	1,750	3,780±35	4,249±35
OS-39187	ODP 1015B, 002H, 07W, 55-57cm	~11.68	Mixed benthics	0.65	6,940±70	1,750	5,190±70	5,950±70
OS-39188	ODP 1015B, 003H, 02W,119-121cm	14.50	Mixed benthics	1.2	8,390±45	1,750	6,640±45	7,543±45
OS-35838	ODP 1015B, 003H 04W, 55-57 cm	16.85	*Neogloboquadrina pachyderma*		9,130±50	800	8,330±50	9,209±50
		22.48[3]	Planktic foraminifera				10,095±135	
		32.24[3]	Planktic foraminifera				12,525±670	
OS-35839	ODP 1015B, 006H 03W, 112-114 cm	44.36	*Uvigerina* sp.		15,950±60	1,750	14,200±60	16,910±60
		56.49[3]	Planktic foraminifera				117,930±340	
OS-35840	ODP 1015B, 008H 03W, 105-107 cm	63.35	*Uvigerina* sp.		21,300±95	1,750	19,550±95	23,060±95
		73.65[3]	Planktic foraminifera				21,755±325	
OS-39189	ODP 1015B, 011H, 01W, 14-16cm	87.95	Mixed benthics	-0.92	29,700±150	1,750	27,950±150	
OS-39190	ODP 1015B, 012H, CCW, 28-30cm	97.59	Mixed benthics	-1.15	33,500±220	1,750	31,750±220	

[1] Ages were calibrated using a reservoir age of 1,750 years for the benthic assemblages as well as for mollusks and 800 and 1,100 years for the planktic foraminiferal samples of less than, and older than, 12,000 radiocarbon years, respectively (following Mix and others, 1999; Southon and others, 1990; Kienast and McKay, 2001).

[2] Calendar ages were calculated using Radiocarbon Calibration Program Revision 4.3 (CALIB 4.3) from Quaternary Isotope Lab, University of Washington based on Stuiver and Reimer (1998).

[3] Unpublished ODP radiocarbon ages (from Behl, oral communication, 1999).

Signals were filtered at 800 to 6,000 Hz and recorded at a 0.25-sec sweep. The data were recorded on magneto-optical disc for later processing as well as on a stable medium using an EPC recorder. Survey speeds of about 7 km/hr provide a variable shot spacing between 1.5 and 2.5 m for the deep-tow boomer profiles.

Selection of coring sites

The coring program conducted in 1998 was part of a major effort to study sediment accumulation and the effects of anthropogenic sediment sources (for example, pollutants) in Santa Monica Bay (Alexander and Venherm, 2003). USGS cruise A-2-98-SC over the basin slope was devoted to box coring in upper slope and shelf areas of Santa Monica Bay (see station information at http://walrus.wr.usgs.gov/infobank/a/a298sc/html/a-2-98-sc.meta.html). As a result, there was only limited ship time for piston-core operations. Six sites on the mid-slope area of the basin margin were adjacent to fold and fault structures that appeared to have recent movement, on the basis of boomer seismic-reflection profiles (fig. 2*B*). This study is based on radiocarbon dating of sediment from ODP Site 1015 and the six piston cores obtained in 1998.

AMS radiocarbon dating

Sediment ages for the six Santa Monica Bay cores were determined by accelerator mass spectrometry (AMS) ^{14}C, using foraminifera and a mollusk (table 1). Because the highest degree of precision possible by AMS dating was not necessary to answer the questions posed in this study, we chose not to use mono-specific planktic foraminiferal samples for age-dating. Instead, the most abundant foraminiferal species in each sample were utilized. As a result, three radiocarbon dates were determined using the benthic species *Uvigerina peregrina* or *Gyroidina altiformis*, nine samples with the genera *Uvigerina* or *Cibicides*, and five samples using a mixed benthic foraminiferal assemblage. Two samples used planktic foraminifera, including one with *Neogloboquadrina pachyderma* and another with a mixed planktic foraminiferal assemblage. In addition, one gastropod was dated in core 361P1. A reservoir age of 1,750 years was chosen for the benthic foraminiferal samples following Mix and others (1999), and similarly applied to the gastropod because it occupied the same substrate as the benthic foraminifera. An 800-year reservoir age was used for the planktic foraminiferal samples because the radiocarbon ages of these samples were younger than 12,000 years (Southon and others, 1990, and Kienast and McKay, 2001). The CALIB 4.3 program (Stuiver and others, 1998) was used to calculate calendar ages from these radiocarbon ages.

Foraminifera were also used to date eleven samples from ODP Hole 1015B. Ten of these used benthic foraminifera, including five samples with *Uvigerina*, and five of a mixed benthic assemblage. One other sample is based on the planktic foraminifera *N. pachyderma*. As with the Santa Monica Bay cores, reservoir ages applied to these samples were 1,750 years for the benthic assemblages and 800 years for the planktics (following Mix and others, 1999; Southon and others, 1990; Kienast and McKay, 2001). Calendar years were again calculated by the CALIB 4.3 program (Stuiver and others, 1998).

We also report four previously unpublished radiocarbon ages on planktic foraminifera obtained by Per Bodén (Department of Geology and Geochemistry, Stockholm University, Sweden) as part of the original ODP investigations. Reservoir ages of 800 and 1,100 years were applied to the planktic foraminiferal samples of less than, and older than, 12,000 radiocarbon years, respectively (Southon and others, 1990; Kienast and McKay, 2001). These radiocarbon dates were converted to calendar years using the CALIB 4.3 program (Stuiver and others, 1998).

Data

The results of the radiocarbon dating are presented in table 1. In addition, the stratigraphic relations of the dates are shown for each core in figures 6 through 11. The geologic setting for each core is discussed and, for the USGS piston cores, the physical properties logs and whole core photograph are also provided.

ODP Site 1015

The primary objective for radiocarbon dating the sediment sequence at Site 1015 was to provide age control for the high resolution sequence stratigraphy developed for Santa Monica Basin (Piper and others, 1999). ODP Site 1015 is located on the flat-lying basin plain at the southeastern end of Santa Monica Basin in water just deeper than 910 m (figs. 1 and 2). The basin plain is underlain by flat-lying turbidite deposits that onlap sediment on the flank of Redondo Knoll to the south (fig. 3). To the north, the stratigraphic section penetrated at Site 1015 pinches out and onlaps the northern margin of the basin. In the section below reflector C, which is the deepest key reflector reached at the drill site, evidence for gas accumulation is indicated by the VAMP-like structure about 2 km south of Site 1015 (fig. 3). Other seismic-reflection profiles in the vicinity of ODP 1015 show additional evidence for gas accumulation at shallow depth in the basin fill (see site survey data in Lyle, 1995). Further, 20 km northeast of the drill site, methane hydrate was recovered from the crest of a mud volcano (Normark and others, 2003). Monitoring of gas composition during drilling showed no evidence for thermogenic sources (Shipboard Scientific Party, 1997).

High-resolution deep-tow boomer profiles across the ODP Site show that the upper 60 m of basin-plain deposits have very low relief locally and gradually thin northward

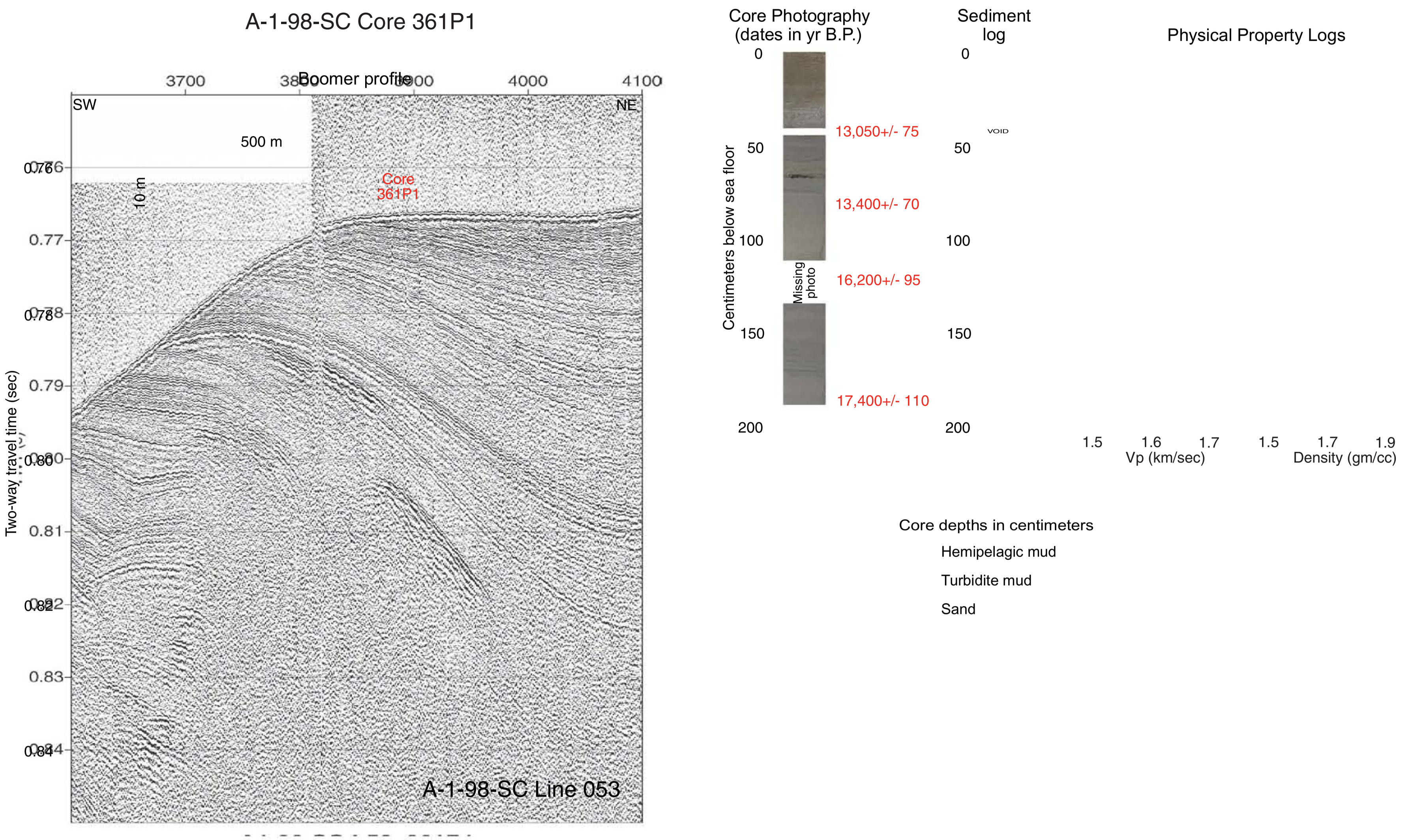


Figure 6. Graphical sediment log for core 361P1 taken during cruise A-2-98-SC. To the left of the sediment log is the deep-tow boomer profile used for siting the core and a whole-core photograph with radiocarbon dates. Bold black line in boomer profile shows buried high-angle fault. The physical-properties logs, P-wave velocity (Vp) and gamma-ray density, are shown to the right. The target depth is shown by the orange-rimmed yellow rectangle.

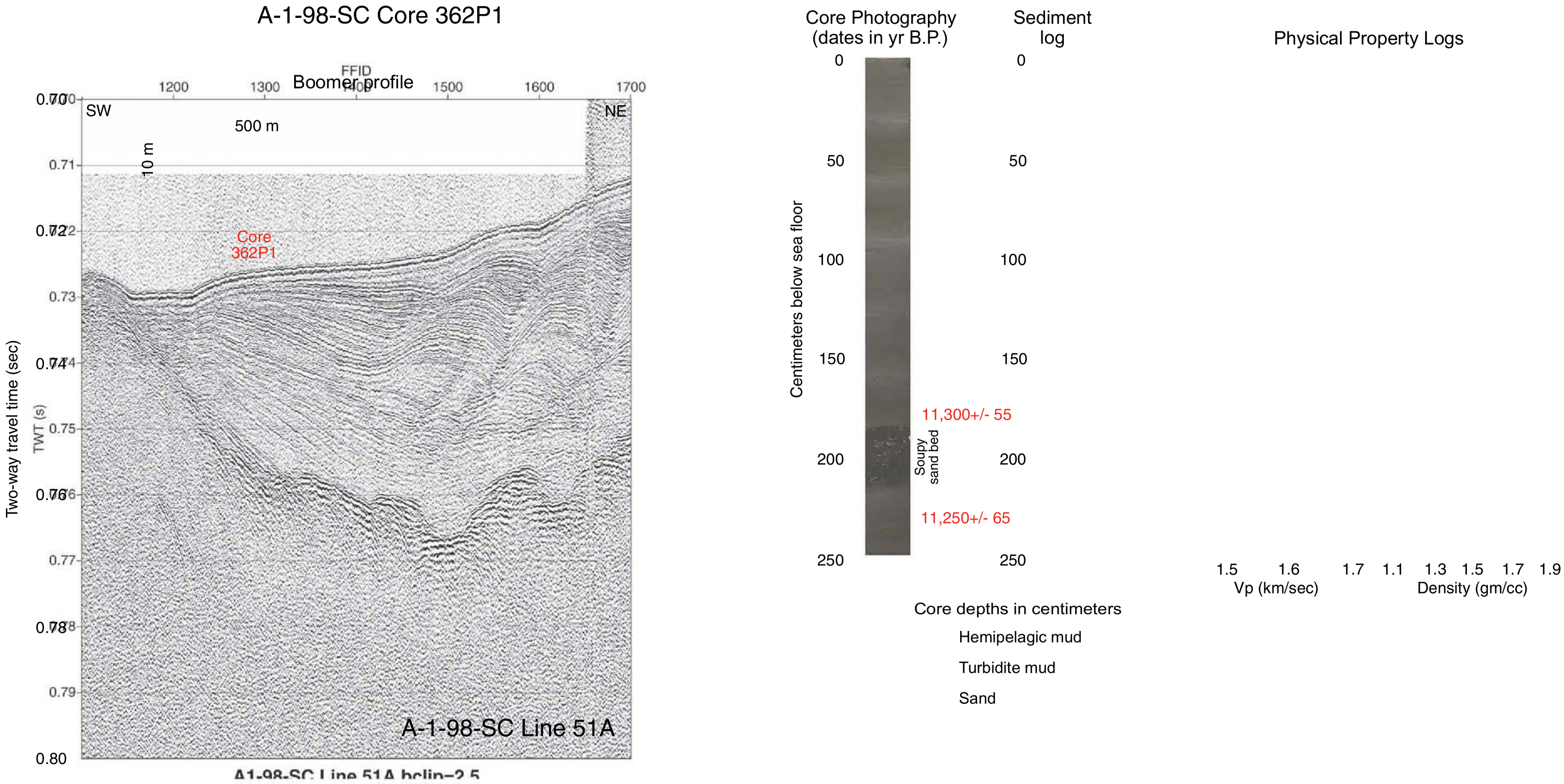


Figure 7. Graphical sediment log for core 362P1 taken during cruise A-2-98-SC. To the left of the sediment log is the deep-tow boomer profile used for siting the core and a whole-core photograph with radiocarbon dates. The physical-properties logs, P-wave velocity (Vp) and gamma-ray density, are shown to the right. Bold black line in boomer profile shows buried fault. The southwest-dipping dashed blue lines denote possible back-rotated slump blocks although their internal bedding is consistent with sediment-wave deposition from currents overflowing from Santa Monica Canyon (see fig. 2*B*). The target horizon is shown by the orange-rimmed yellow rectangle.

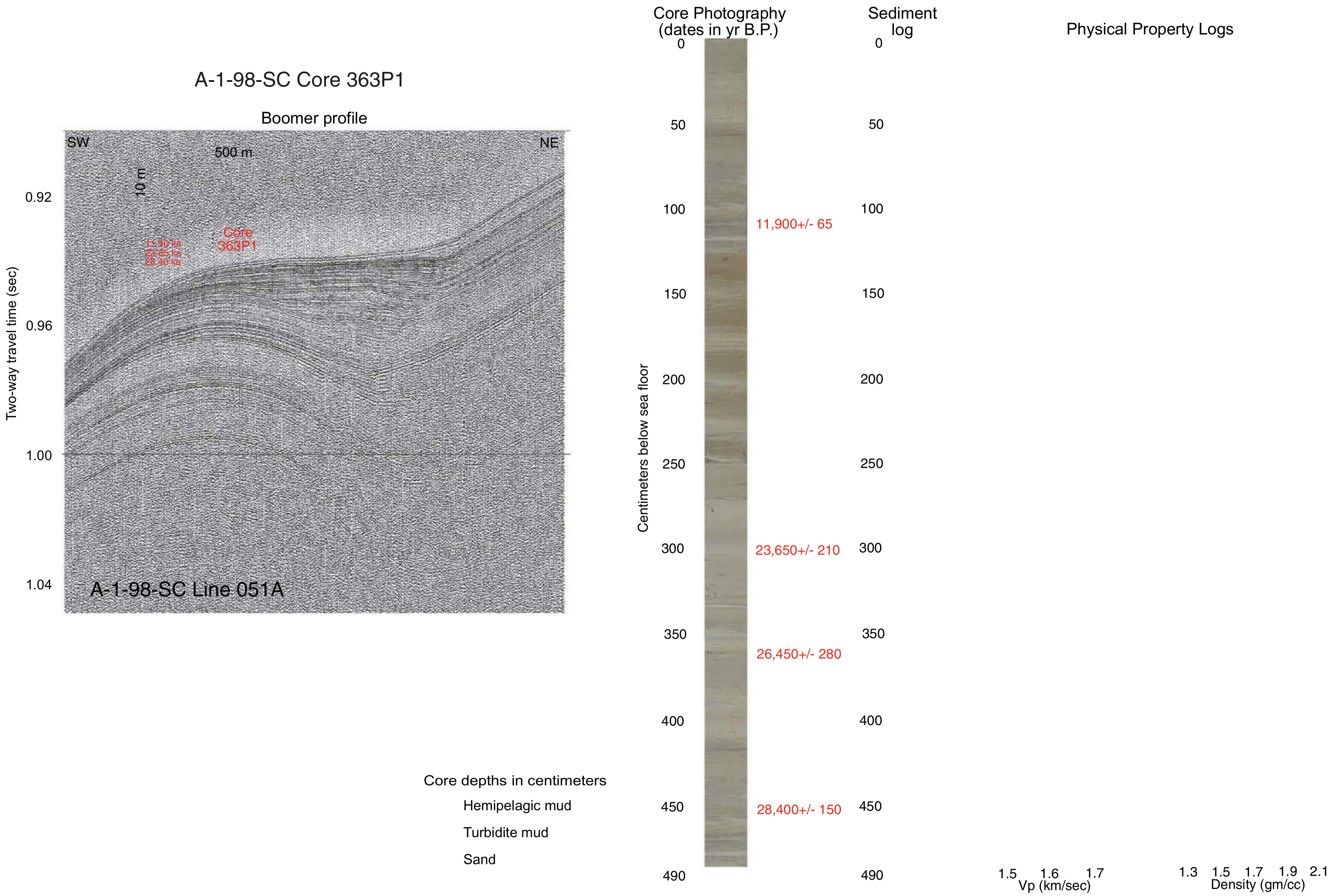


Figure 8. Graphical sediment log for core 363P1 taken during cruise A-2-98-SC. To the left of the sediment log is the deep-tow boomer profile used for siting the core and a whole-core photograph with radiocarbon dates. The physical-properties logs, P-wave velocity (Vp) and gamma-ray density, are shown to the right. The target depth is shown by the orange-rimmed yellow rectangle.

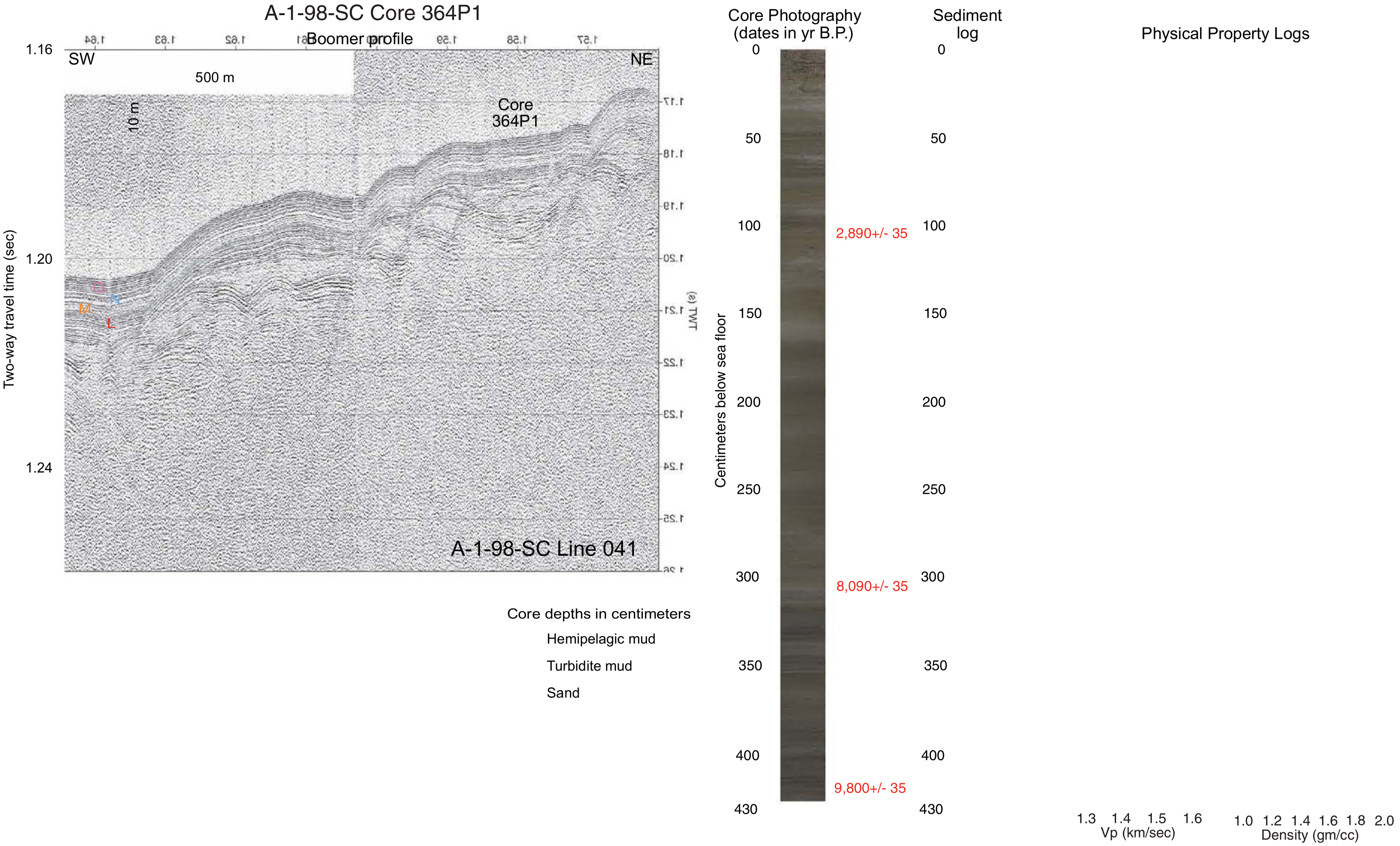


Figure 9. Graphical sediment log for core 364P1 taken during cruise A-2-98-SC. To the left of the sediment log is the deep-tow boomer profile used for siting the core and a whole-core photograph with radiocarbon dates. The physical-properties logs, P-wave velocity (Vp) and gamma-ray density, are shown to the right. Bold black lines in boomer profile show possible buried faults; sea floor offsets have been smoothed by draping of sediment starting just before key reflector L was deposited. The target depth is shown by the orange-rimmed yellow rectangle.

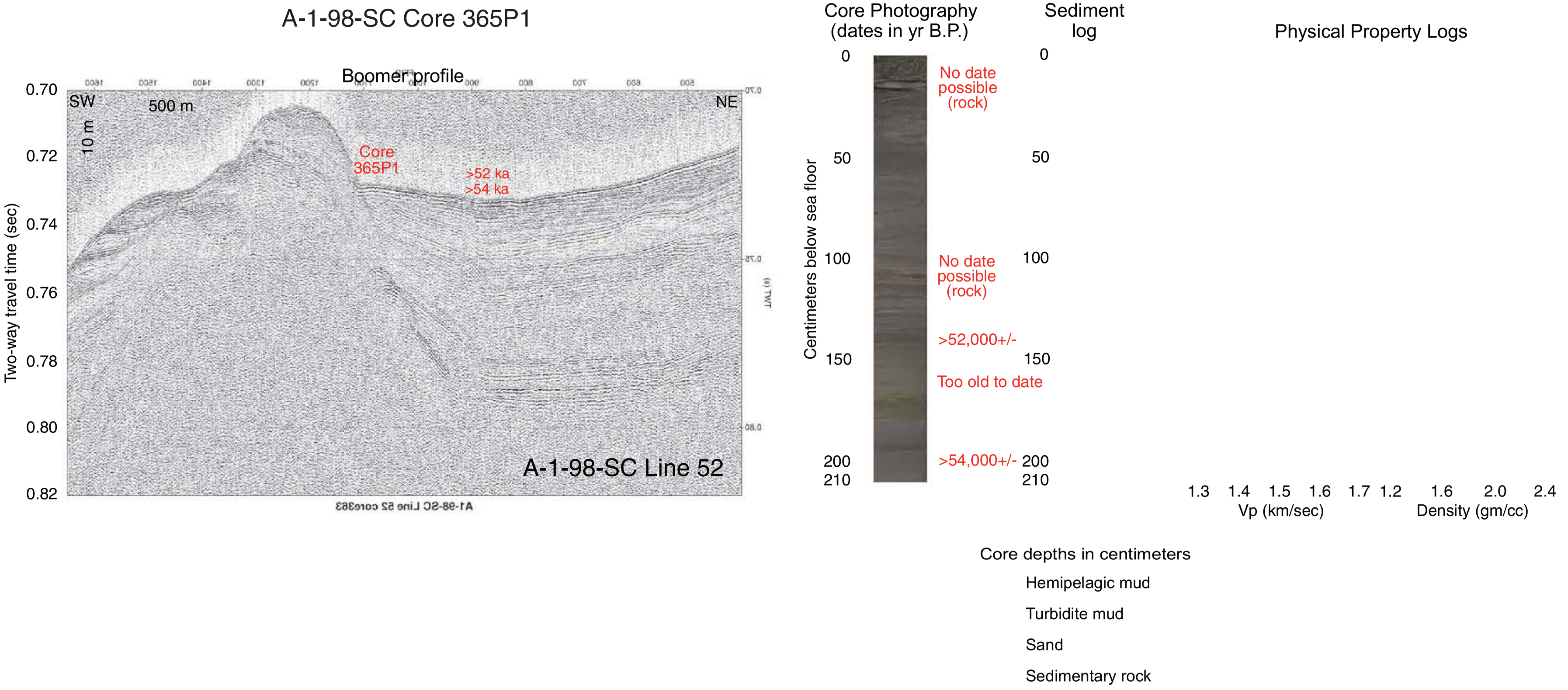


Figure 10. Graphical sediment log for core 365P1 taken during cruise A-2-98-SC. To the left of the sediment log is the deep-tow boomer profile used for siting the core and a whole-core photograph with radiocarbon dates. The physical-properties logs, P-wave velocity (Vp) and gamma-ray density, are shown to the right. The older age of the samples at this site suggests that the sediment is talus from the faulted anticlinal fold immediately southwest. Bold black line in boomer profile shows buried fault. The top of the north-dipping section, which was the target horizon, is shown by the orange-rimmed yellow rectangle.

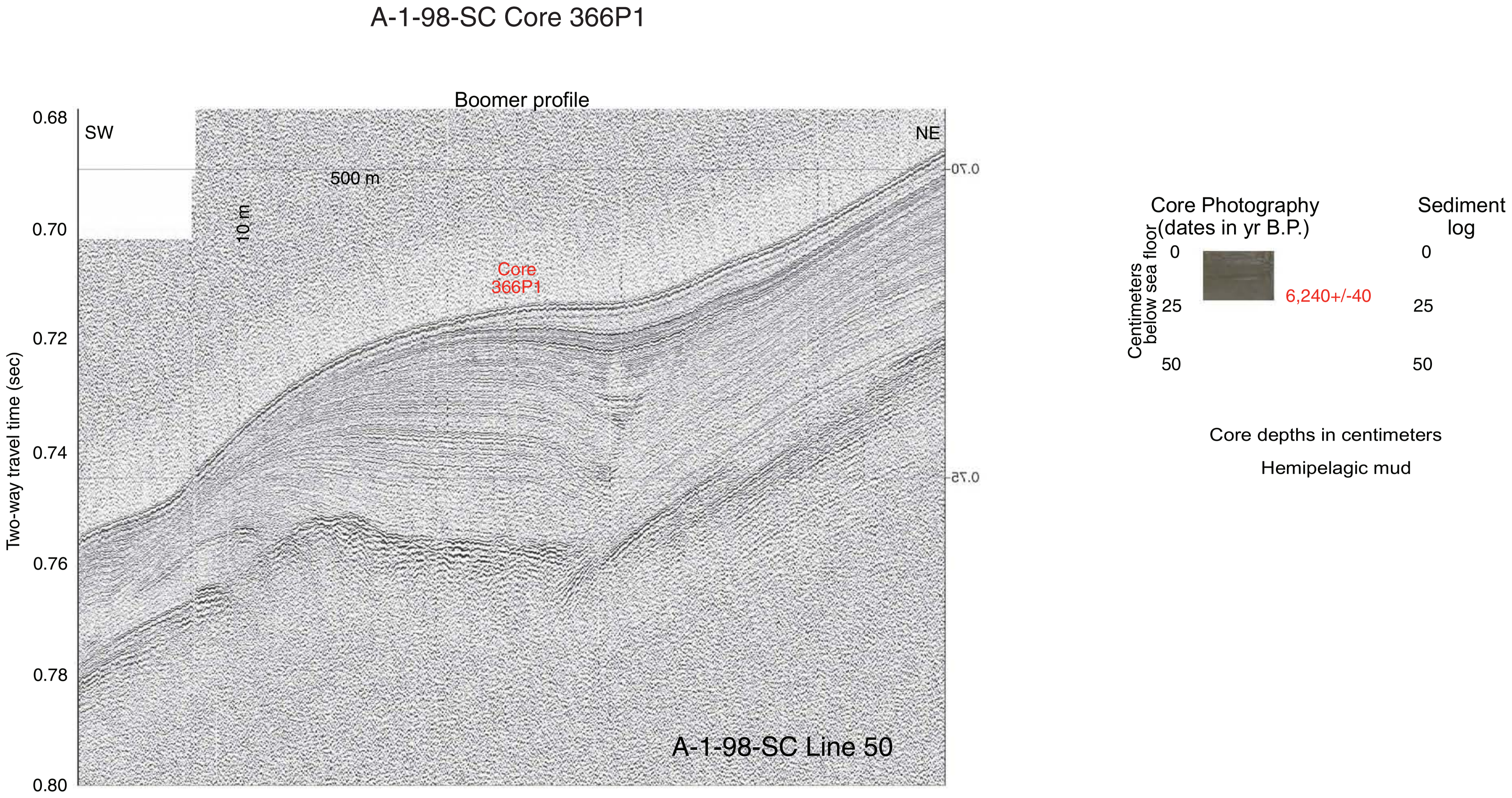


Figure 11. Graphical sediment log for core 366P1 taken during cruise A-2-98-SC. To the left of the sediment log is the deep-tow boomer profile used for siting the core and a whole-core photograph with radiocarbon dates. The target horizon is shown by the orange-rimmed yellow rectangle.

toward the basin (fig. 4). The bulk of the sediment in the upper part of Santa Monica Basin was derived from the Hueneme Canyon area at the west end of the basin (Normark and others, 1998; Piper and others, 1999; Piper and Normark, 2001). The acoustic character of the reflections in this area is typical of that for ponded basin turbidite facies (Piper and others, 1999).

Two holes were drilled at the ODP site in Santa Monica Basin; Hole 1015A reached 149.5 meters below the sea floor (mbsf) and Hole B bottomed at 97.8 mbsf (Shipboard Scientific Party, 1997). The sediment log (fig. 5) is based on the Visual Core Description (VCD) forms used by the Leg 167 sedimentologists. Although core recovery exceeded 90 percent at Hole 1015A, some intervals were disturbed sufficiently that the sediment log constructed for this site is a composite of both holes. The log intervals from 32 to 40 mbsf, 56 to 63 mbsf, 74 to 79 mbsf, and 91 to 97 mbsf are based on Hole 1015A; otherwise, the VCDs for Hole 1015B are used. The sediment log depicts only the upper 100 m at this site because we were unable to find datable material deeper in 1015A. All samples obtained for radiocarbon dating under this study were taken from Hole 1015B.

Beds in the upper 100 m of sediment cored in the basin plain are dominantly silt or sand (~70 percent). Two muddier intervals with generally thinner sand beds occur between 7 and 16 mbsf and 52 and 84 mbsf (fig. 5). The lower 50 m cored in Hole 1015A is mostly sand, which contributed to the problem of finding datable carbonate. The average sediment accumulation rate at the ODP site is about 3 mm/y, and this rate holds even after sea-level rise during the Holocene.

Core site 361P

Core station 361 is located at the northwestern end of a fold ridge on the mid-slope, adjacent to a narrow pass that leads to the deeper basin floor (figs. 2*B* and 6). The goal was to date the upper part of a sequence of well-bedded sediment that appears to be faulted and uplifted to form a bench on the slope (fig. 2*B*). The core is less than 2 m in length, however, and thus it failed to reach the primary objective, which was a dipping horizon at about 6 mbsf. During the short interval of the latest Pleistocene that was sampled, deposition of sand beds was common but only muddy sediment represents the Holocene.

Four intervals from this core were dated (fig. 6 and table 1). The shallowest dated interval is from a whole-round sample that was taken for geotechnical studies. The sediment remaining after the geotechnical evaluation was sieved for foraminifera for dating. Assuming that the core recovered the mudline (that is, the water/sediment interface), the Holocene accumulation rate is less than 0.03 mm/y, which is two orders of magnitude less than on the basin floor. The latest Pleistocene rate for the underlying sand-rich interval is 0.33 mm/yr.

Core site 362P

Core station 362P is north of a fold ridge on the mid-slope where a layer of acoustically transparent sediment wedges out and overlies a northward-dipping section of sediment. The acoustic character of this wedge suggests turbidite deposits (figs. 2*B* and 7; see Piper and others, 1999). The turbidite section appears truncated and is unconformably overlain by the sediment drape. The objective for coring at this site was to sample the truncated and tilted turbidite sequence. The core sampled a graded sand bed at 2 m depth, confirming that the tilted turbidite section was reached by the core.

Both dated intervals in core 362P1 are basically from the Pleistocene-Holocene boundary and are effectively the same age, within the radiocarbon-age error limits (fig. 7 and table 1). The two dates bracket a graded sand bed tending to confirm that turbidite deposition can be considered instantaneous with respect to geologic time. The Holocene accumulation rate for the mud above the sand bed is 0.16 mm/yr.

Core site 363P

Core station 363P is sited on the same deep-tow boomer profile as for 362P but is about 150-m deeper water depth than core site 362P (figs. 2*B* and 8). The site was selected to sample the top of a gently folded section of well-bedded sediment. The folded section is overlain by a horizontal sequence that is ponded on the northeast side of the fold but thins abruptly on the basinward (southwest) limb of the underlying fold. The core is nearly 5 m in length but might not have sampled the shallowest reflector that is associated with the fold structure.

The well-bedded unit ponded behind the fold consists of thin sand and silt beds and turbidite mud. The coarser beds tend to thin and fine upwards, and the shallowest silt bed is just below the Pleistocene-Holocene boundary (fig. 8 and table 1). Only mud is deposited above this silty bed, and the Holocene accumulation rate is about 0.095 mm/yr. The deposits with sand and silt beds was deposited during marine oxygen isotope Stage 2 (Martinson and others, 1987) at a rate of 0.21 mm/yr. The age of the beds at the bottom of the core suggests that the fold was essentially in its present form by about 30 ka.

Core site 364P

Core station 364P is from the lower slope of the north side of Santa Monica Basin, about 40 m above the basin plain (figs. 2*B* and 9). This site was selected to sample the bedded sequence in which key reflectors from L to O can be traced continuously through deep-tow boomer profiles from ODP 1015 (see tracklines in fig. 1). On the basin floor, the interval above reflector L consists of numerous thin- to thick-bedded sand units; hemipelagic mud beds are more common in the interval from 6 to 16 mbsf (fig. 5). Core 34P1 recovered more than four meters of sediment and confirmed that turbidity currents are able to deposit sediment well above the floor of the basin. Similar to the correlative sequence in ODP 1015, the middle part of the core consists of mostly hemipelagic mud; graded silty mud and fine sand beds are common in the section below 3 mbsf in core 364P1.

Three radiocarbon dates from this core show the entire core is Holocene in age (fig. 9 and table 1). The sediment accumulation rate is 0.43 mm/yr, which is the highest for any of our cores from the continental slope.

Core site 365P

Core station 365P is north of a folded and fault-bounded ridge on the mid-slope. Similar to the setting for core site 362P, there is a layer of sediment that wedges out to the southwest (toward the ridge) and unconformably overlies a northeast-dipping section of relatively well-layered sediment (figs. 2*B* and 10). The northeast-dipping section under the unconformity appears truncated at or near the base of the uplifted ridge. The objective for coring at this site was to sample the truncated and tilted sequence.

The core sampled just over two meters of sediment with medium to thick-bedded sand in the upper 70 cm. Indurated sediment (rock) was penetrated at two levels, and our attempts to date the sequence only determined that the sediment is older than 50 ka (fig. 10 and table 1). The older dates and the presence of sedimentary rock fragments within the core suggest that much of the cored material may be debris from the fault scarp bounding the north side of the uplifted ridge. The core apparently did not penetrate deeply enough to sample the northeast-dipping sedimentary section, the objective for this site.

Core site 366P

Core station 366P is on a mid-slope bench near the Santa Monica Canyon (figs. 2B and 11). The objective at this site was to penetrate the toe of an acoustically transparent sediment drape that pinches out southwestward across the margin of the mid-slope bench. The key-reflector sequence defined for the Santa Monica Basin floor indicates that most of the sediment filling the basin during the late Quaternary has come from the west end of the basin (Normark and others, 1998). Santa Monica Canyon does not appear to be a major pathway for sediment transport (Piper and others, 1999). The acoustically transparent drape is thought to be Holocene hemipelagic mud overlying well-layered sediment that might be overbank deposition from Santa Monica Canyon.

The core obtained was too short to address the objectives at this site, and no physical property logs were attempted because of its short length. The mud recovered is late Holocene (fig. 11 and table 1), but the Holocene accumulation rate is less than 0.04 mm/yr, assuming that the core recovered the water/sediment interface. Because the transparent layer is just over 2 m thick at the target site, the base of the layer would be nearly 60 ka, which is unlikely. It seems probable that the piston core did not sample the sediment-water interface at the sea floor and the radiocarbon date represents some interval deeper in the transparent layer.

Discussion

The high-resolution seismic-stratigraphy defined for the Santa Monica Basin floor and the base-of-slope areas can be combined with the radiocarbon chronology for ODP Site 1015 to date movement on faults and landslides (figs. 5 and 12). In addition, these data can be used to help construct a sediment budget for the late Quaternary using the results of previous work in the Santa Monica Bay area (see for example, Alexander and Venherm, 2003; Sommerfield and Lee, 2003, 2004).

The deep-tow boomer profiles in figure 12 are taken from data collected by the Geological Survey of Canada. These data highlight examples that are chosen to show the utility of a basin-wide chronostratigraphy for Santa Monica Basin, should new high-resolution reflection profiles be collected to extend the seismic-hazard analysis farther seaward. An example of a buried landslide on the northern flank of Redondo Knoll is from an area between boomer profiles collected by the USGS (figs. 1 and 12*A*). The small landslide came to rest on a surface that is about 3 m above reflector J (measured along the left-hand side of fig. 12*A*). The slide mass is onlapped by a reflector that is about three meters below reflector K, which in turn onlaps the highest part of the slide mass. Thus, the failure event probably occurred about 12 ka (fig. 5).

The second example is from the western margin of the basin that falls outside the work area of the USGS earthquake hazard task (figs. 1 and 12*B* and *C*). A major fault marks the southwestern margin of Santa Monica Basin at the base of the Santa Cruz-Catalina Ridge. The structure in this part of the basin remains poorly defined, however, and the fault shown in figure 12*B* lies within the basin sediment fill, east of the main fault trace along the Santa Cruz-Catalina Ridge. Locally, narrow depressions have formed over this fault suggesting transtension in this area (figs. 1 and 12*B*). The youngest deformed reflection surface lies just below key reflector O; sedimentation above reflector O has resulted in a gradual filling of the depression above the fault. As seen from figure 5, the time of the most recent offset is approximately 2 ka. In contrast, the deeper penetration sleeve-gun profile in figure 12*C* defines a steeply dipping fault that cuts the surface of a shallow anticlinal structure, thus suggesting transpression along the fault. The northeastern flank of the anticline is onlapped by key reflectors B to J, which show little evidence for penecontemporaneous folding. The growth of the anticlinal structure thus predates the oldest sediment dated in this study and might be as old as 90 ka (see key reflector ages in Normark and others, 1998). When the change from transpression to transtension occurred on this structure is not determined with available data except to be sometime post reflector J (fig. 12*C*).

Although the usefulness of the chronostratigraphic control provided by radiocarbon dating of samples from ODP Site 1015 is easy to demonstrate, the effectiveness of short, conventional piston cores is more problematic. In general, the limited depth of sampling as a result of coring malfunction or the core hitting hard (including unconsolidated sand) substrate limits the overall success rate. For example, stations 361P, 363P, and 366P did not provide constraints on the timing of deformation (figs. 6, 8, and 11). Core 362P1 was successful in confirming that the sediment drape was Holocene in age but did not sample to a sufficiently great depth to provide an age for the tilted and truncated section, which may be pre-Holocene in age (fig. 7). Core 365P1 provided no age control for the folding or faulting, but the age of the sediment recovered (>50 ka) suggests that older sediment is exposed and being shed from the adjacent uplifted ridge (fig. 10).

Core 364P1 was the most successful of the wire-line piston cores attempted for this study. This core confirmed that the stratigraphy from the well-dated ODP Site 1015 could be locally extended onto the lower slope (fig. 9). Thus, it should be possible to date offsets on structures adjacent to the basin floor. It has also been thought that rates of uplift of basin sediment might be used to determine strain on Borderland faults (Normark and Piper, 1998; Fisher and others, 2003). Although this approach has some applicability, caution must be used because the significance of Core 364P1 is that it shows that silt and sand beds from turbidity currents are being deposited on the lower slopes of the basin a minimum of 40 m above the basin floor. Intervals of thick sands on the basin floor have correlative fine-grained turbidites on the basin margins, whereas intervals with only thin sands on the basin floor lack identifiable turbidites (compare the sediment logs in figs. 5 and 9). The thicker turbidity currents such as those that deposited sand 40 m above the basin floor at 364P1 probably deposit silt and mud as much as 50 to 100 m above the basin floor. It is important to remember that the same key reflector beds observed to extend to core site 364P1 are also found on the overbank area of the Hueneme fan valley at comparable elevations above the channel floor. Apparently elevated or dipping sections of turbidite beds that are found above the basin floor are, therefore, not necessarily the result of tectonism.

Sommerfield and Lee (2004) showed that sediment-accumulation rates on the shelf and upper slope of Santa Monica Bay began to decrease between 12 and 9 ka after having been maximal ca. 15 to 10 ka, which they observed was after the interval of greatest sea-level lowering (ca. 18 ka). They argued that sea-level rise above the shelf break led to transgressive sedimentation on the shelf reducing sediment supply to the slope-basin area. The record documented by our new radiocarbon dates at ODP Site 1015, however, shows that there is limited correspondence between accumulation rates on the upper slope and shelf in Santa Monica Bay and that on the deep basin floor. For example, the maximum accumulation rate of about 4mm/yr on the basin floor lasted from 22 to 8 ka, thus encompassing both the last glacial maximum lowering and most of sea-level rise during the Holocene (fig. 5). Although the accumulation rate on the basin plain decreased to about 1 mm/yr for about 4 millennia, by 4 ka, the accumulation rate was again high (~3 mm/yr). This indicates that sedimentation in the Santa Monica Bay area is not a reliable indicator of rates in the adjacent deep basin, in this case because the delta-fed Hueneme Canyon (and not the much closer Santa Monica Canyon) is the dominant source for the deep basin.

Conclusions

This study presents 28 new radiocarbon dates for sediment from the Santa Monica Basin. The new radiocarbon dates include 17 from six piston cores on the northeastern margin of the basin and 11 from ODP Site 1015 on the basin floor. These dates provide an improved understanding of the changes in sediment supply to the basin as a result of sea-level rise from the late Pleistocene to current highstand condition. The study confirms a high sediment accumulation rate for the Santa Monica Basin floor, averaging more than 3.1 mm/yr for the last 32 ka. During the marine oxygen-isotope Stage 2 lowstand, the sediment accumulation rate reached 4 mm/yr. Although the rates dropped to about 1 mm/yr during the mid-Holocene, during the last few thousand years, the accumulation returned to about 3 mm/yr. The Hueneme Canyon at the west end of the basin remains the dominant sediment source even during highstand conditions. These new radiocarbon dates also provide chronologic control for a high-resolution basin-wide stratigraphic framework. Preliminary results using these dates show Holocene-age landslide and fault activity within the basin.

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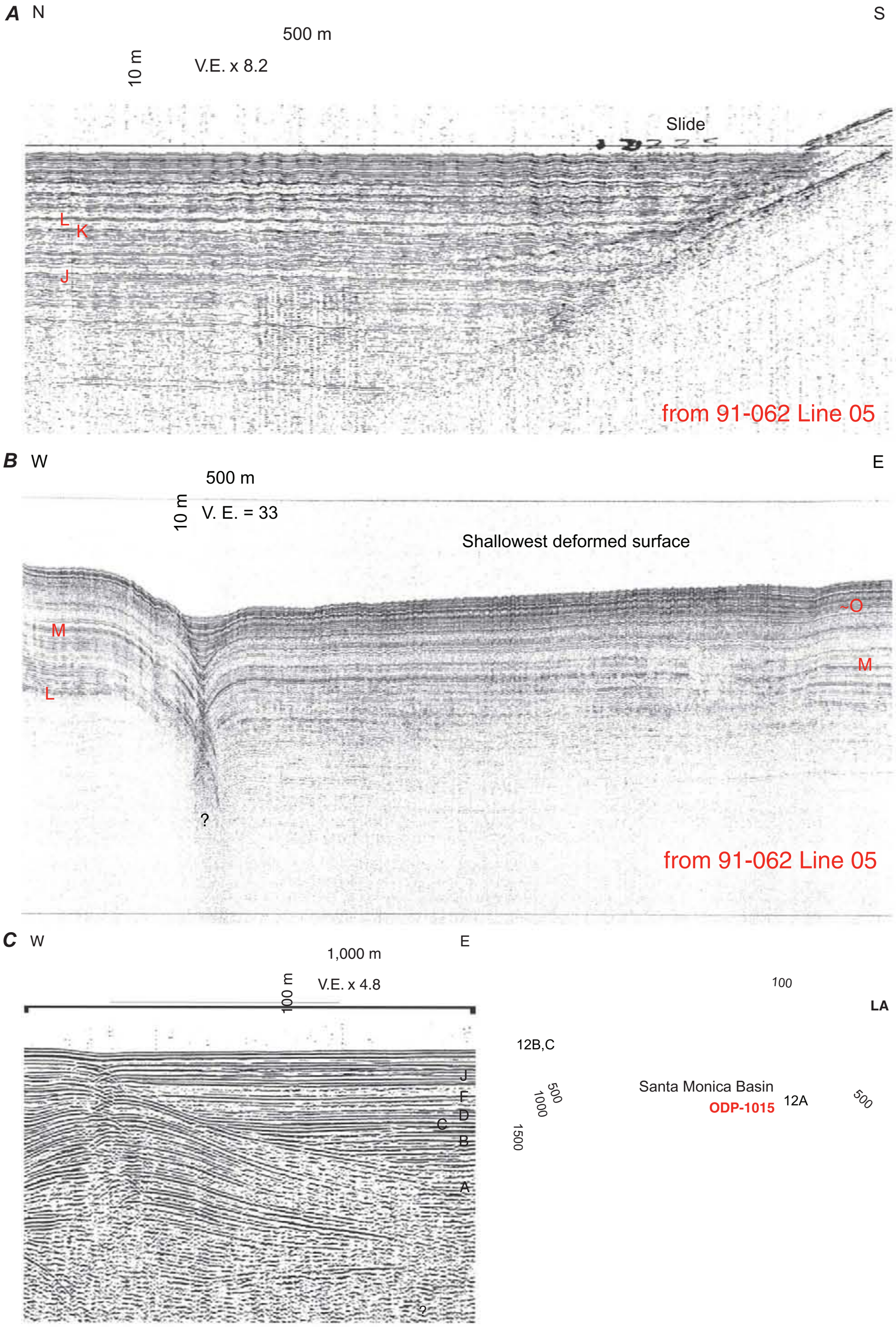

Figure 12. Along the lower slopes and floor of Santa Monica Basin mass wasting and fault offsets can be dated using a high-resolution boomer (Huntec) stratigraphy correlated with ODP Site 1015. See figures 1 and inset map above for location of profiles. *A*, In this example, the wedge-shaped landslide deposit is resting on a surface that is about 2 m above reflector J. The top of the slide unit is completely covered by the time reflector K was deposited. The slide probably occurred about 11 or 12 ka. *B*, The youngest deformed surface over this basin margin fault is just below horizon O, or about 2 ka. Above this surface, sediment is draping the gently-sloping sea floor and gradually filling the depression along the fault. Below this surface, the thickness of the units is the same in the depression as it is on the margins of the depresession. *C*, This sleeve-gun profile shows the deeper structure related to the shallow features depicted in the Huntec profile in B. Deeper key reflectors are shown for reference. V.E., vertical exaggeration. LA, Los Angeles.

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