Geological Society of America Special Papers

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Geological Society of America Special Papers 2009;454; 251-269
doi:10.1130/2009.2454(4.3)

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The Geological Society of America
Special Paper 454
2009

Submarine landslides of the Southern California Borderland

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ABSTRACT

Conventional bathymetry, sidescan-sonar and seismic-reflection data, and recent, multibeam surveys of large parts of the Southern California Borderland disclose the presence of numerous submarine landslides. Most of these features are fairly small, with lateral dimensions less than ~2 km. In areas where multibeam surveys are available, only two large landslide complexes were identified on the mainland slope—Goleta slide in Santa Barbara Channel and Palos Verdes debris avalanche on the San Pedro Escarpment south of Palos Verdes Peninsula. Both of these complexes indicate repeated recurrences of catastrophic slope failure. Recurrence intervals are not well constrained but appear to be in the range of 7500 years for the Goleta slide. The most recent major activity of the Palos Verdes debris avalanche occurred roughly 7500 years ago. A small failure deposit in Santa Barbara Channel, the Gaviota mudflow, was perhaps caused by an 1812 earthquake. Most landslides in this region are probably triggered by earthquakes, although the larger failures were likely conditioned by other factors, such as oversteepening, development of shelf-edge deltas, and high fluid pressures. If a subsequent future landslide were to occur in the area of these large landslide complexes, a tsunami would probably result. Runup distances of 10 m over a 30-km-long stretch of the Santa Barbara coastline are predicted for a recurrence of the Goleta slide, and a runup of 3 m over a comparable stretch of the Los Angeles coastline is modeled for the Palos Verdes debris avalanche.

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Lee, H.J., Greene, H.G., Edwards, B.D., Fisher, M.A., and Normark, W.R., 2009, Submarine landslides of the Southern California Borderland, *in* Lee, H.J., and Normark, W.R., eds., Earth Science in the Urban Ocean: The Southern California Continental Borderland: Geological Society of America Special Paper 454, p. 251–269, doi: 10.1130/2009.2454(4.3). For permission to copy, contact editing@geosociety.org.

INTRODUCTION

The slopes of the Southern California Borderland have long been identified as an ideal location for the occurrence of submarine landslides. Some of the slopes are steep, owing at least in part to their origin near thrust and strike-slip faults. Also, a relatively large part of the seafloor is a slope environment because of the small size of the basins and narrow shelves. Sediment-accumulation rates, particularly along the mainland slopes, are relatively high because of rapid uplift of coastal mountains, high suspended-sediment loads during the winter storm runoff of short, steep rivers, and the relatively high erodibility of much of the coastal and inland terrain. Finally, the area is highly active seismically, indicating large downslope, seismically induced stresses and strength loss in sediment as a result of cyclic loading.

The study of submarine landslides is important because they are a hazard to offshore development, as indicated by the collapse of offshore drilling rigs (Bea et al., 1983), breaking of submarine cables and pipelines, and destruction of coastal facilities by landslides that cross the shoreline. Also, if their size, location, and motions fall within a critical range, they can produce damaging tsunamis. Perhaps the best known recent example of these is the tsunami that struck Papua New Guinea in 1998. Post-tsunami investigations led to the conclusion by most researchers (e.g., Okal and Synolakis, 2001; Synolakis et al., 2002; Tappin et al., 2003) that the tsunami was caused by a large offshore landslide that was in turn produced by a M 7.0 earthquake. Other well-known tsunamis were also caused by landslides, including the tsunami that struck Newfoundland following the 1929 Grand Banks earthquake (Heezen et al., 1954; Mosher and Piper, 2007), many of the tsunamis that damaged coastal communities in Alaska during the 1964 earthquake (Hampton et al., 1993; Lee et al., 2006), and aseismic tsunamis in Skagway, Alaska, in 1994 (Rabinovich et al., 1999) and Nice, France, in 1979 (Seed et al., 1988). Finally, submarine landslides, and the debris flows and turbidity currents into which they can evolve, are an important component of offshore sediment transport as well as a key part of the source-to-sink system that ultimately produces sediment depositional bodies within basins (e.g., refer to papers in this volume, Section 2).

The objective of this paper is to review and describe recognized submarine mass movements within the Southern California Borderland and assess the potential for future events that may well result in tsunami generation and impacts to the coastal and marine infrastructure. The paper first considers the methods that are used to identify, classify, and date submarine landslides. Next, the paper describes early landslide mapping surveys that relied on older technologies. With this information as a background, the paper reviews landslides mapped using modern multibeam imagery and also considers potential failure deposits in areas that fall into gaps between multibeam images. Finally, the paper considers the potential that landslides of these scales have toward tsunami generation and speculates on the causes of failure and differences in landslide morphology.

METHODS OF IDENTIFICATION AND DATING

Submarine landslides are easily recognized when they intersect the shoreline, disrupt or destroy offshore facilities, or when major changes in water depth or seafloor relief are directly observed. The detection and recognition of most submarine landslides, however, including those in Southern California, rely on interpretation of remote observations of seafloor and subbottom morphology. Developments in offshore remote-sensing technologies, such as precision depth recorders, high-resolution, seismic-reflection and sidescan-sonar systems, and multibeam bathymetric mapping techniques, have allowed the marine investigator to determine accurately the appearance of the seafloor and map areas of instability. High-resolution, seismic-reflection profiling allows us to look at the geometry of subbottom acoustic reflectors and discern distorted and broken bedding suggestive of mass-wasting events. Nondistorted bedding, separating distorted intervals, likely corresponds to intervening periods of nonfailure between failure events.

Of these developments, multibeam bathymetric-mapping technology is one of the most significant. Such technology (Hughes-Clarke et al., 1996) involves projecting many narrow beams of sound at different angular directions from a surface ship, towed body, or underwater vehicle. Reflected beams are received back at the source and used to determine the water depth along an almost continuous swath beneath the vessel. The resulting soundings are of sufficient density that little interpolation is needed to produce the details of the physiographic surface. An estimate of acoustic backscatter from the seafloor is obtained by calibrating and correcting the amount of energy contained in the returning signal. Backscatter intensity provides important information on the geologic character of the seafloor.

When the above techniques show that a mass-wasting deposit exists on the seafloor, other techniques are used to determine its age. Generally, dating mass-transport complexes requires an estimate of the age of unfailed sediment either overlying or underlying the deposit. The age of the overlying deposit is probably most accurate because the failure event may have incorporated previously deposited sediment at its base.

In Southern California, two Ocean Drilling Program (ODP) sites (893 and 1015) are located near submarine landslides. Well-developed chronologies within these sites can be extrapolated based on correlation with seismic reflections. Even without continuous reflections, accumulation rates in the ODP sites can be assumed to apply within the immediate vicinity.

Without nearby borehole or well control, piston cores can be positioned to sample sediment representative of the material overlying the submarine landslides. If enough of the sediment column is sampled, the chronology established for the cores using age determination techniques, such as radiocarbon dating, is used to date the mass-transport complex. See Normark et al.

(this volume, Chapter 2.6) for additional information on core chronology in the Southern California Borderland.

LANDSLIDE TERMINOLOGY

The terminology recommended by Varnes (1958) is commonly used to classify mass movements whether they are on land or under water. According to this system, "slides" are movements of essentially rigid, internally undeformed masses along discrete slip planes. "Slumps" are a kind of slide in which blocks of failed material rotate along curved slip surfaces, and "translational slides" involve movement on a planar surface. Slides can become "flows" as the failed mass progressively disintegrates and loses its internal structure. The material begins to behave like a viscous liquid. "Debris flows" are flows in which the sediment is heterogeneous and may include larger clasts supported by a matrix of fine sediment. "Mud flows" involve predominantly muddy sediment. When landslides disintegrate into blocky pieces and have clearly moved very rapidly without a channel, they are referred to as "debris avalanches." In the sections below, the Varnes (1958) system is commonly applied, although in a few cases the traditional name for a feature is used rather than a name that would reflect its proper classification. The "Goleta slide" is an example of a traditional name for a feature that is perhaps best described as a large debris flow.

EARLY STUDIES OF SUBMARINE LANDSLIDES IN SOUTHERN CALIFORNIA

Emery and Terry (1956) conducted the first study that considered submarine landslides in Southern California. They fortuitously conducted their study on one of the largest and most significant landslide complexes in Southern California—the Palos Verdes debris avalanche (Bohannon and Gardner, 2004; Locat et al., 2004). Emery and Terry (1956) used an echo sounder to produce profiles of bottom topography over the feature. They recognized that the slope contained landslide deposits by observing gullies in the upper slope and a hummocky apron at the base, but they could not recognize the scale of the failure or the details of its morphology, given the primitive nature of acoustic soundings available at the time. A figure by Gorsline et al. (1984), based on subsequent acoustic profiles, gives a somewhat improved view of the feature (Fig. 1B). It does not, however, adequately define the source region or show the locations of most recent failure, all of which can be seen in multibeam images (Fig. 1A; Bohannon and Gardner, 2004; Lee, 2005). Gorsline et al. (1984) report that the failure is 100–500 years old. More recent radiocarbon data show that the latest significant failure within the landslide complex occurred ~7500 years ago (Normark et al., 2004).

Most studies directed toward mapping submarine landslides in Southern California were conducted in the 1970s and early 1980s in response to interest in developing petroleum resources in the area (Greene et al., 1975; Ploessel et al., 1979; Richmond et al., 1981; Clarke et al., 1983). These were augmented by investigations conducted by the University of Southern California (Haner and Gorsline, 1978; Nardin et al., 1979; Gorsline et al., 1984; Thornton, 1986). Lease sales were planned, specifically Numbers 35 and 48, and there was a need to identify potential hazards to development in the lease blocks. The geologic hazards identified in the lease areas included faults, seismicity, slumps, landslides, and creep (Greene et al., 1975). Generally a survey grid with an ~1–2 km spacing was laid out within established lease sale areas. High-resolution, seismic-reflection profiles were obtained along these lines, and sediment samples were obtained with grab samplers or, occasionally, box or gravity corers. Failure features were interpreted from seismic-reflection records by noting hummocky surfaces, headwall scarps, compressional ridges, transverse (tensional) cracks, evidence of rotation, and/or the presence of slip surfaces (Clarke et al., 1983). Areas of apparent failure were mapped (e.g., Greene et al., 1975; Ploessel et al., 1979; Clarke et al., 1983) and delineated as potential hazards to offshore development. In a limited number of cases, detailed studies of individual failure features or small areas were conducted (Field and Clarke, 1979; Edwards et al., 1980, 1995). In two cases, these included a quantitative analysis of failures using geotechnical techniques (Edwards et al., 1980; Lee and Edwards, 1986).

These early studies showed that mass-wasting processes play an important role in basin filling in Southern California, and failures occur at many scales from very small to quite large (many km on a side) (Field and Edwards, 1980; Field, 1981; Field and Edwards, 1993). Some larger failure zones are composed of a set of smaller failures. "Continued, episodic loading of the sediment produces local inhomogeneous, weakened sediment masses" (Field and Edwards, 1980). This episodic loading may contribute to the formation of large failure areas of the kind commonly identified by conventional acoustic mapping techniques. A map showing the locations of identified failures within the Southern California Borderland was constructed by Field and Edwards (1980), and a modified version (Fig. 2) was given by Field and Edwards (1993). Note that the distribution of failures in the map is somewhat dependent upon where detailed surveys were conducted. That is, mapping was not conducted uniformly but rather focused on areas of societal interest, e.g., lease sales. These areas of interest tend to show the most landslides. The California Continental Margin Geologic Map Series (Greene and Kennedy, 1987) also shows locations of many offshore slope failures based on the same extensive data set from the 1970s and early 1980s.

RECENT STUDIES OF SUBMARINE LANDSLIDES IN SOUTHERN CALIFORNIA

In the early 1980s, a moratorium was placed on offshore oil drilling in California, thereby terminating almost all interest in offshore geologic hazards in Southern California. Some work on synthesizing existing data continued for the next 15 years, as discussed above, but few new data were gathered. Ultimately, new maps of the seafloor were produced between the late 1990s and the present, using multibeam technology (Gardner and Mayer,

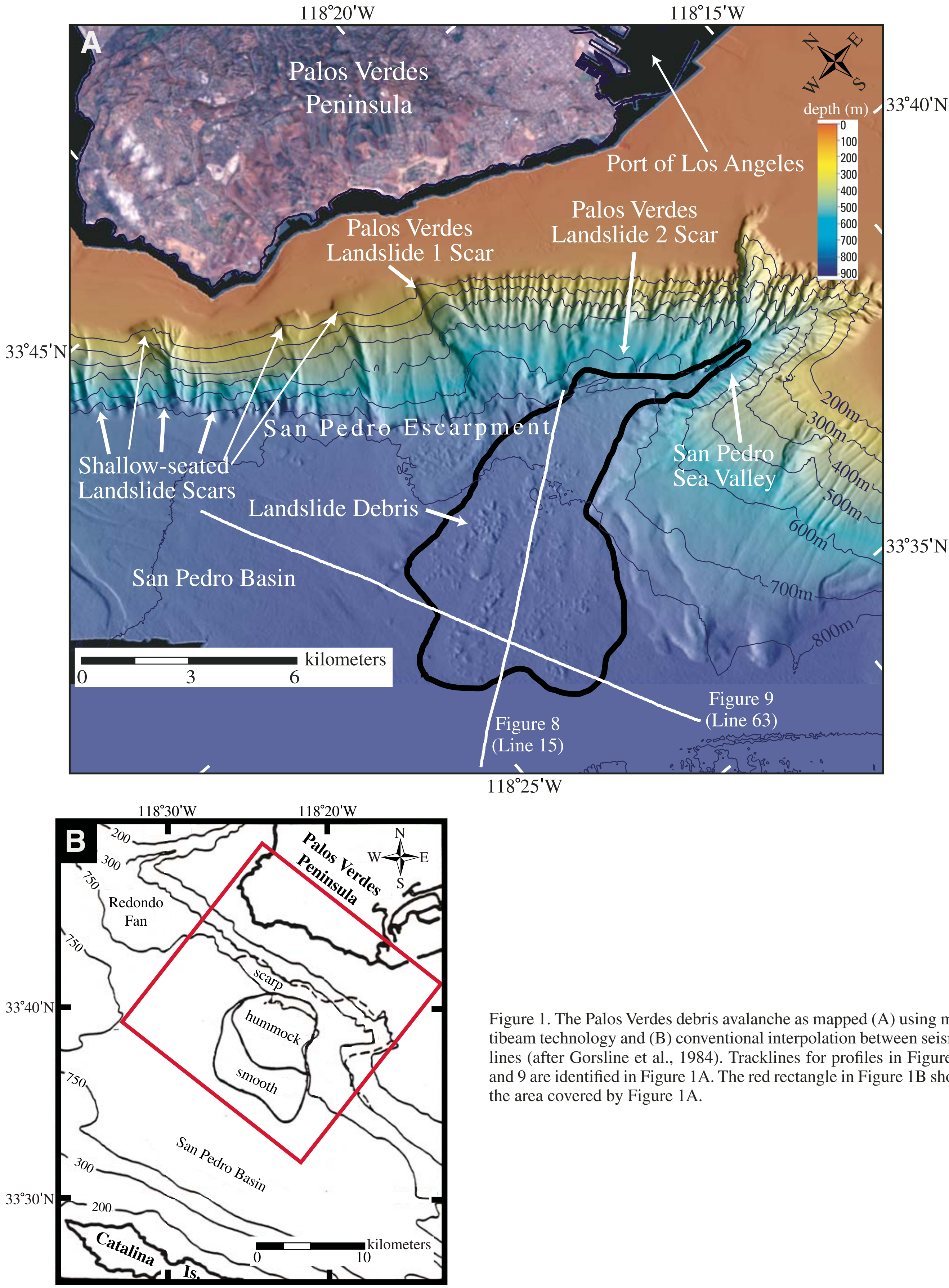

Figure 1. The Palos Verdes debris avalanche as mapped (A) using multibeam technology and (B) conventional interpolation between seismic lines (after Gorsline et al., 1984). Tracklines for profiles in Figures 8 and 9 are identified in Figure 1A. The red rectangle in Figure 1B shows the area covered by Figure 1A.

1998; Gardner et al., 1999, 2002, 2003; Eichhubl et al., 2002; Dartnell et al., 2006; Dartnell and Gardner, this volume). These maps cover much of the inner part of the Borderland but none of the outer banks and basins (Fig. 3). Multibeam images provide a vastly improved view of the seafloor. Because multibeam coverage is essentially complete, the full character of surface features is apparent (to within the footprint of the system used), without the need for interpolation between tracklines (contouring). Mapping is automatic and does not require the intervention of human judgment and possible bias.

By comparing multibeam images with earlier landslide distribution maps, we can better appreciate the approximations associated with the earlier interpretations. For example, in Figure 1, which shows images of the Palos Verdes margin, both approaches

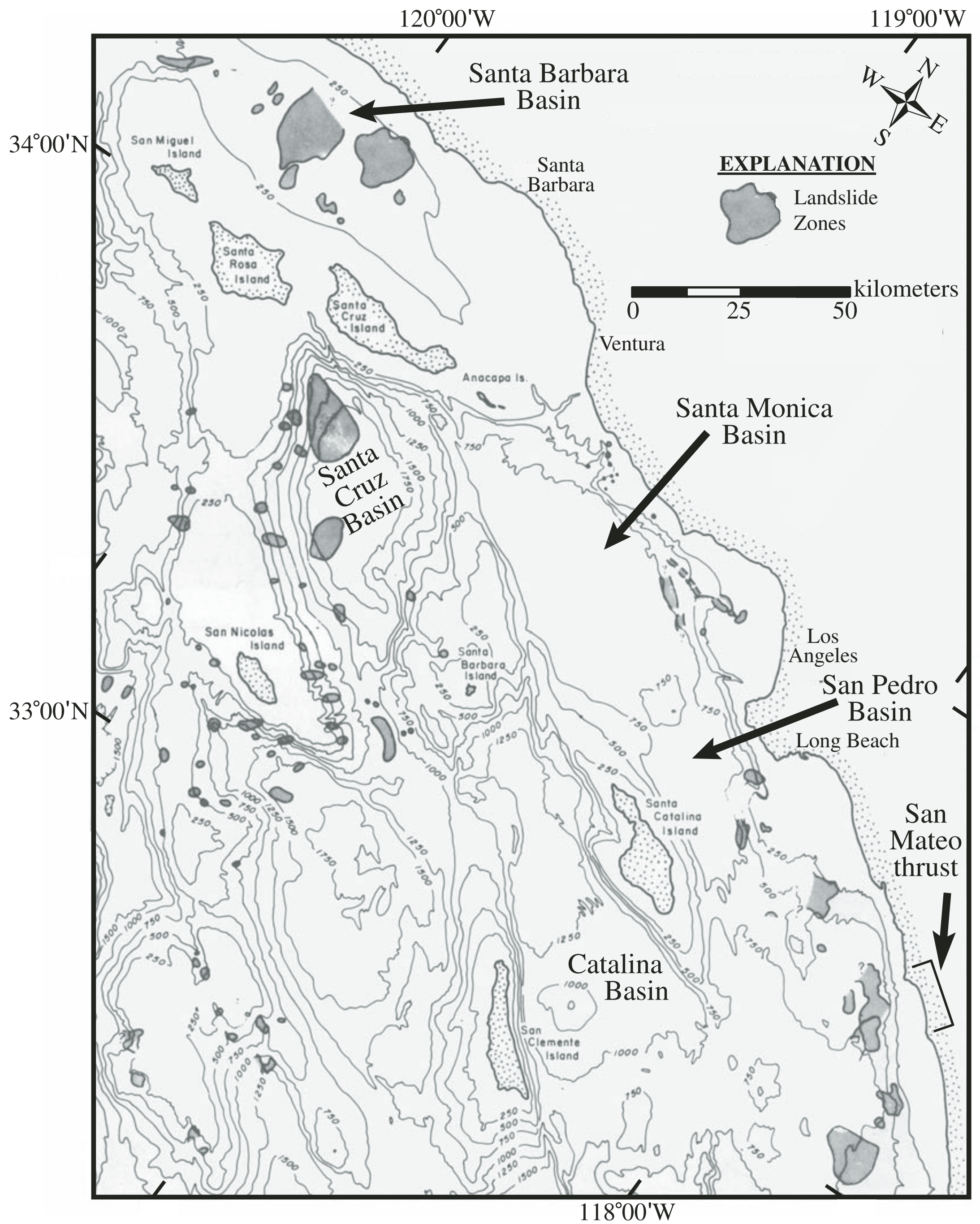

Figure 2. The distribution of submarine landslide deposits based on surveys from the 1970s (after Field and Edwards, 1980).

show submarine landslides, but the new multibeam image shows vastly more detail, including the intricate gullying on the slope scar, the presence of well-defined components that are apparently more recent failures, and the blocky debris field below the failed slope. The image also shows other smaller, shallow-seated landslides to the west of the main failure. In the Santa Barbara Channel (upper left part of Fig. 2; Fig. 4), both the earlier distribution map and the modern multibeam image show the existence of large landslides. The Goleta slide, as shown on the multibeam image of Figure 4, likely corresponds to the easternmost of the two large slides shown off Santa Barbara in Figure 2. However, the even larger "landslide" shown to the west in Figure 2 appears in Figure 4 as an area of channels related to a relict late Pleistocene (ca. 500 ka) turbidite system called the Conception fan (Kraemer, 1986; Fischer and Cherven, 1998; Normark et al., this volume, Chapter 2.7). Some of the other identified "landslides" compare with features that look like landslides in Figure 4, but others do not. In summary, maps of submarine landslides produced mainly in the 1970s and early 1980s and discussed above provide some information about the distribution of these features, but they need to be used with caution. Modern multibeam maps are essential for detailed landslide investigations.

Three large multibeam images (Fig. 3) cover a length of ~290 km along the mainland slope (out of a total length of ~375 km). These images cover much of the Santa Barbara Channel (Eichhubl et al., 2002; Greene et al., 2006), Los Angeles margin (Gardner et al., 2002, 2003), and San Diego margin (Dartnell et al., 2006). Within these mapped areas, there are only two large deep-seated landslide complexes with lateral dimensions greater than 5 km: (1) Goleta slide, Santa Barbara Channel (Eichhubl et al., 2002; Fisher et al., 2005; Greene et al., 2006) and (2) Palos Verdes debris avalanche (Bohannon and Gardner, 2004; Locat et al., 2004; Normark et al., 2004). As landslide complexes, they both include multiple events that have left deposits shaping the seafloor morphology, and additional events that left buried deposits that indicate failures extending back over 100,000 years. There are many small, shallow-seated landslides identified, particularly in Santa Barbara Channel and south of the Palos Verdes Peninsula. Also, several of the submarine canyons that have been mapped using multibeam (e.g., Redondo, Newport, and La Jolla) show the remains of failures on their walls.

There is evidence of failures outside of the areas mapped using multibeam bathymetry. The major landslides and landslide complexes identified using multibeam imagery are discussed in

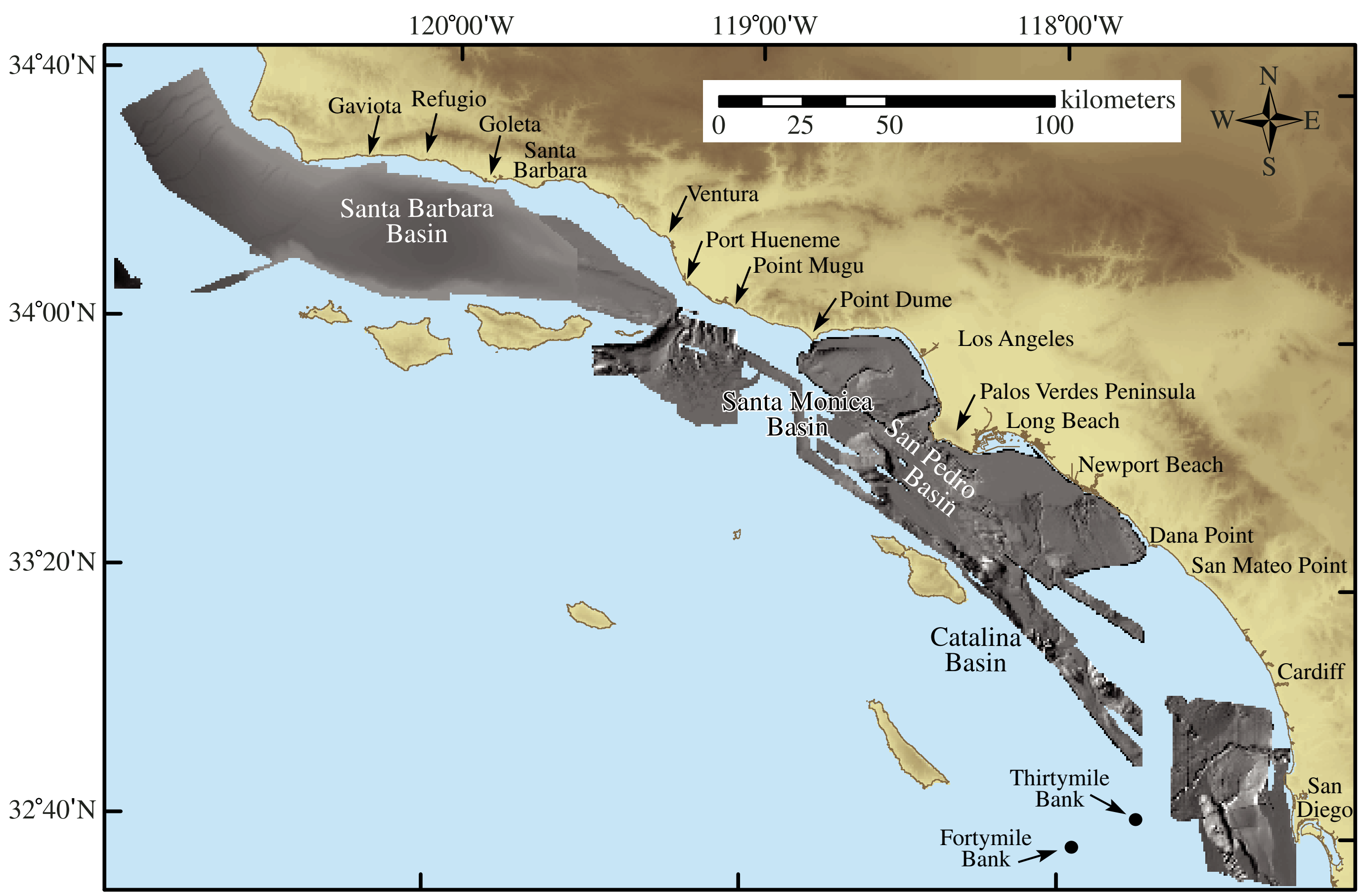

Figure 3. The Southern California Continental Borderland showing major features and present extent of multibeam mapping coverage.

more detail below. Likewise, discussions are provided of sections of the Borderland and specific features that are of particular concern as landslide hazards.

SUBMARINE LANDSLIDES IDENTIFIED USING MULTIBEAM IMAGERY IN OFFSHORE SOUTHERN CALIFORNIA

Santa Barbara Channel Area: Overview

Extensive investigations were carried out on two landslide deposits located in the Santa Barbara Channel, southwest of the city of Santa Barbara, California (Fig. 4). Santa Barbara Basin is the major physiographic feature within Santa Barbara Channel with a maximum water depth of 589 m. It is a margin basin without canyons that is undergoing north-south compression. It is the most northerly of a series of basins and, unlike others to the south, it is oriented east-west rather than northwest-southeast. The orientation is the result of subduction and growth of the Transverse Ranges (Fisher et al., this volume, Chapter 4.4). The basin floor is generally flat, with less than a 0.4° slope. The steepest slopes of the basin are located along its northern and southern flanks; an average slope of 2.5° is found on the northern flank, and 1.7° on the southern flank. Numerous faults and folds exist in the Santa Barbara Basin and generally trend east-west (Greene et al., 2006). Evidence of active and dormant fluid seeps, including active venting of gas and oil, bacterial mats, precipitates of authigenic carbonate, and mud and tar volcanoes, have been observed in the Santa Barbara Basin (Luyendyk, 1998; Eichhubl et al., 2002).

Sediment input to the basin is fine grained with most of the basin beneath 200 m water depth containing less than 10% sand (Greene et al., 2006). The fine-grained sediment (silt and clay) accumulates along the northern flank of the Santa Barbara Basin having been transported northwestward along the shelf and over the shelf edge to produce a prograding shelf edge. Sedimentation rates along the northern flank of the Santa Barbara Basin range from 1.7 m/k.y. on the shelf and upper slope to 2.0–2.5 m/k.y. within the lower to mid-slope areas (Thornton, 1984; Edwards et al., 1995; Eichhubl et al., 2002).

Ocean Drilling Program (ODP) site 893 was drilled to 196.5 m near the center of the Santa Barbara Basin (Fig. 4), only ~1 km from the toe of the major Goleta submarine landslide complex, discussed below. Seismic-reflection horizons dated by correlation to ODP site 893 follow into sediment overlying nearby landslides to provide estimates of the ages of these landslides. Radiocarbon dating of foraminifers from cored sediment indicates

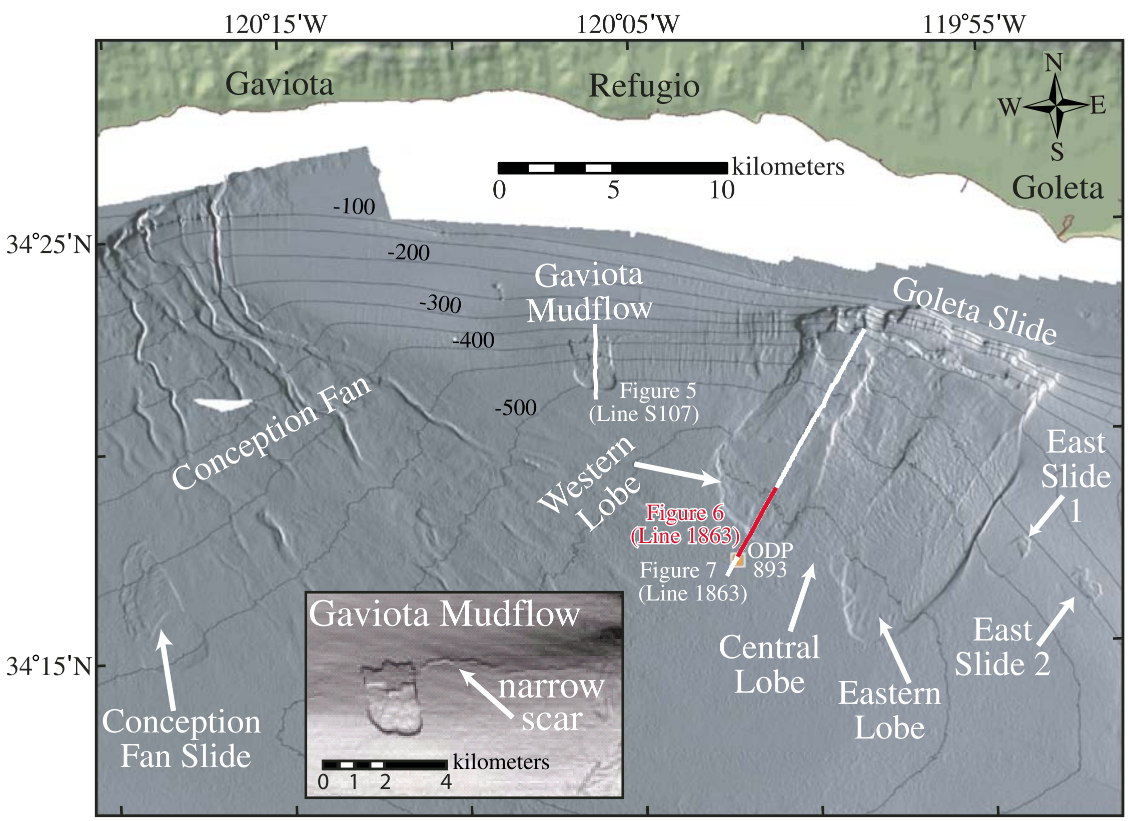

Figure 4. Multibeam image of landslide complexes in Santa Barbara Basin (courtesy of the Monterey Bay Aquarium Research Institute). The figure shows the Gaviota mudflow, the multi-lobed Goleta slide, the location of Ocean Drilling Program (ODP) site 893, and tracklines for profiles shown in Figures 5–7. Also, shown in the insert, is a narrow scar (possibly a propagating head scarp), extending eastward from the Gaviota mudflow.

a near linear sedimentation rate of 1.45 m/k.y. extending back as much as 30,000 years (Ingram and Kennett, 1995). Recent unpublished radiocarbon dating of 1.5- to 5-m-long piston cores from the basin slope north of the ODP site showed sedimentation rates varying from 0.8 to 1.9 m/k.y. Lower rates are associated with the steeper upper slope and higher rates with the lower slope and basin floor (as also reported by Gorsline et al., 1984).

The Santa Barbara Basin region is seismically active (Yerkes et al., 1981), and 15 earthquakes equal to or greater than M 5.0 were recorded over the past 200 years in the immediate area (Toppozada et al., 2000). The largest historical earthquakes (Fisher et al., this volume, Chapter 4.2) within the Santa Barbara Basin region occurred in 1812 (M 7.1 and 7.5) and 1925 (M 6.8). The December 21, 1812 earthquake caused extensive damage to the Spanish missions and reportedly caused high waves (McCulloch, 1985; Borrero et al., 2001). Reports of tsunami runup from the event are inconsistent, but the runup appears to have been as much as 4 m at Refugio, 40 km west of Santa Barbara, and 2 m in Santa Barbara (Borrero et al., 2001).

Santa Barbara Channel: Gaviota Mudflow

By far the most significant submarine landslide feature in Santa Barbara Channel is the Goleta slide (Fig. 4). However, there are also several clearly defined, shallow-seated landslides including the Gaviota mudflow, the Conception fan slide, and east slides 1 and 2 (Fig. 4). These shallow-seated failures have the dimensions of a few km on a side, a nearly planar failure surface, a depth to the failure surface of ~10 m, and clearly defined failure scars and hummocky mass-wasting deposits. The Gaviota mudflow (Fig. 4) lies in 380–500 m of water on the mainland slope. The deposit was first identified by Duncan et al. (1971) and was described in detail by Edwards et al. (1995), Eichhubl et al. (2002), and Greene et al. (2006). The morphology and internal geometry of the mudflow were first defined using high-resolution, seismic-reflection data (Fig. 5) in combination with core samples. Sediment failure occurred on a 4° slope in the uppermost part of late Quaternary well-bedded slope deposits. The failure zone occupies an area of 4 km^2 and involved the translation of 0.01–0.02 km^3 of sediment. Major geomorphic features of the mudflow deposit include a 6- to 8-m-high headscarp, a scar 50–700 m wide, and a main body 1 km long and 12 m thick. The hummocky surface of the mudflow deposit, the chaotic internal structure, and the bulbous toe tapering upslope to a thin tail are consistent with mass flow involving extensive internal deformation.

A geotechnical analysis incorporating the results of both static and dynamic triaxial strength tests showed that the sediment was statically stable before the landslide was triggered (Lee and Edwards, 1986). Failure, therefore, was probably caused by a strong, nearby earthquake causing development of excess pore pressure and reduced sediment shear strength. The weakened sediment that remained after the earthquake shaking continued to flow down the gentle basin slope under the stresses generated by gravity alone until it stopped on a slope of ~1° (Lee et al., 1992).

Sediment failed in stages, ending with upslope retrogressive retreat of the headwall along the east side of the failure zone. These multiple stages could have occurred in rapid succession following a single earthquake or, conceivably, spaced over many

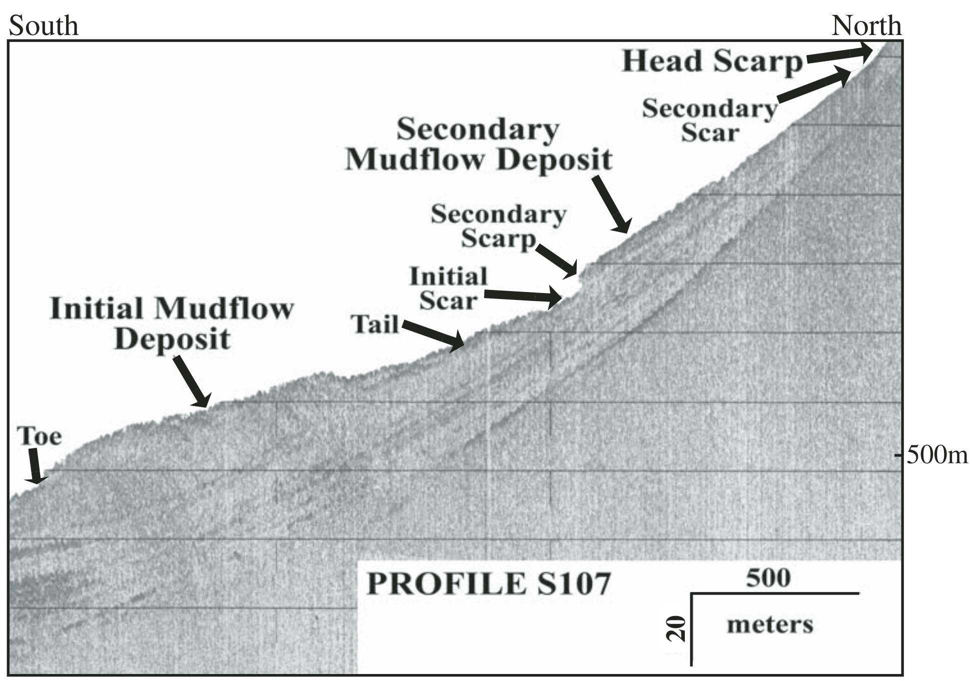

Figure 5. High-resolution subbottom profile (location shown in Fig. 4) of the Gaviota mudflow (after Edwards et al., 1995).

years and related to multiple earthquakes. A thin (~0.5 m thick) sediment cap presently rests on the scar surface, is recognized by physical properties (factor of three lower shear strength than that of the sediment from the scar) and likely represents post-failure deposition. Assuming that the accumulation rate ranges from 0.8 to 1.9 m/k.y., corresponding to recently dated piston cores, then the most recent shear failure along the scar surface likely occurred between 250 and 600 years ago. The latest shear failure could have been somewhat more recent because the event would have suspended considerable sediment that would enhance initial sediment accumulation on the scar. Also, the scar is a depression that could trap sediment and would likely have a higher accumulation rate than the surrounding terrain. Accordingly, the 1812 earthquake could possibly have triggered the most recent shear failure related to the Gaviota mudflow. This could either have been the only failure event related to this deposit or the most recent of a series of retrogressive failures. A distinct narrow scar (possibly a propagating head scarp) extends from near the eastern head wall of Gaviota mudflow for over 2 km eastward. This feature likely represents either an incipient failure or a remnant of the previous failure.

Santa Barbara Channel: Goleta Slide

The Goleta slide complex (Fig. 4) is a series of slope failures that together are 14 km long and 11 km wide with a Holocene displacement volume of 1.5–1.75 km^3 (Eichhubl et al., 2002; Fisher et al., 2005; Greene et al., 2006). The complex has as many as 24 individual minor or major failure units expressed on its surface (Greene et al., 2006). However, these units appear to be components of only three major segments (lobes), the eastern, central, and western segments, which are composed of distinct head scars, blocks, and displaced masses. Each segment likely relates to an individual retrogressive failure, although each could also have consisted of multiple failures that were relatively close in time. These three lobes constitute most of the relatively recently failed material, and they are roughly equal in volume, each having a volume of ~0.5 km^3 (Greene et al., 2006). The lobes could perhaps best be classified as "debris flows" given their chaotic structure and flow-like nature. However, the term "Goleta slide" has been used extensively in the literature and will continue to be used in this chapter. ODP site 893 (Kennett, 1995), is located ~1 km southwest of the toe of Goleta slide and can be used to gain control of the age of the failures. Chirp seismic-reflection data obtained over the ODP drill site and the toe of the western lobe of the Goleta landslide (Fig. 6) show that a thin (0.01 s, ~8 m) sediment layer covers the landslide. On seismic-reflection sections, this layer appears similar to the shallowest sediment drilled at the ODP site. If the two sediment layers have comparable accumulation rates (1.45 m/k.y. for the ODP site, as discussed above), then the landslide is covered by sediment that is ~6 k.y. old. A somewhat different age for the western lobe was obtained by Fisher et al. (2005), who identified a tongue of landslide debris extending outward from the toe of the lobe. Based on interpretation of strata thicknesses lying above the tongue, an estimated age of 8 ka was determined.

A number of mass-transport deposits underlie the western lobe of the Goleta landslide. These older deposits are late Pleistocene, on the basis of oxygen-isotope data from ODP site 893 (Kennett, 1995). Drilling data indicate that some of the underlying mass-transport deposits are at least as old as 164 k.y.; the maximum age obtained from drilled rock and sediment (Fisher et al., 2005). Thus, the Goleta slide does not represent a single

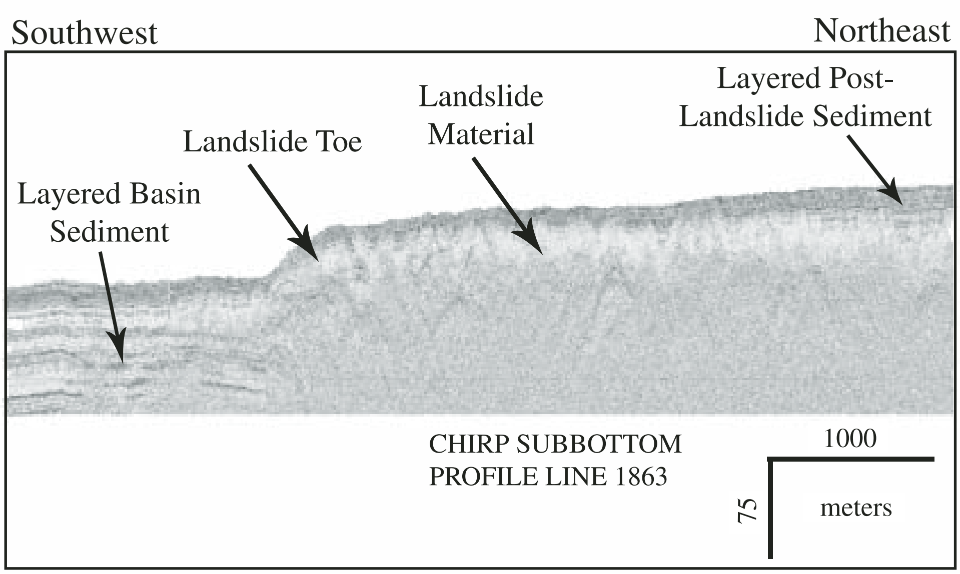

Figure 6. High-resolution, chirp, subbottom profile of the toe of the west lobe of the Goleta side complex showing layered sediment overlying distorted landslide debris (location of profile shown in Fig. 4). Ocean Drilling Program (ODP) site 893 is located at the left margin of this figure.

failure, isolated in time, but instead represents the latest in a series of slope failures.

Three of these older failures lie above reflector “A,” which is estimated to have an age of ca. 160 ka (Fig. 7). Four additional failures lie below reflector “A.” Ages estimated from piston coring of nearby outcrops (Nicholson et al., 2006; Normark et al., this volume, Chapter 2.7, Fig. 3) indicate that the age of the oldest failure is ca. 410 ka (Fig. 7). Accordingly, the recurrence interval for failures of the western lobe is greater than 50 k.y. If the three lobes have comparable recurrence intervals and if they move independently of each other, as proposed by Greene et al. (2006), then the recurrence interval for individual major failures within the Goleta complex is on the order of 15 k.y.

San Pedro Basin: Palos Verdes Debris Avalanche

The San Pedro Basin (Fig. 1A) lies directly south of the main part of the City of Los Angeles and the Ports of Los Angeles and Long Beach. San Pedro Basin has a maximum water depth of around 800 m, is fed by several submarine canyon systems, and contains thick deposits of sandy turbidites (Normark et al., this volume, Chapter 2.7). The 25-km-long mainland slope, along the northeast boundary of the San Pedro Basin, south of the Palos Verdes Peninsula, is particularly steep (11.5° to 17°) and has been termed the San Pedro Escarpment (Bohannon and Gardner, 2004). The area south of the eastern part of the San Pedro Escarpment is identified as the San Pedro Sea Valley and follows the axis of a syncline that parallels the foot of the slope. An anticlinal structure parallels the shelf break, with an axis ~5 km to the northeast (Dibblee, 1999). The escarpment itself approximately follows the dip of the rocks connecting the axes of the anticline and the syncline. This configuration, as well as the steepness of the slope, is highly conducive to the development of submarine landslides (Fisher et al., 2004).

The region surrounding the San Pedro Escarpment is active seismically. Twelve earthquakes with magnitudes greater than 5.0 have occurred within 80 km of the area in the past 200 years (Yerkes, 1985; Fisher et al., this volume, Chapter 4.2). Perhaps the most significant recent earthquake was the 1933 Long Beach earthquake, which caused major damage to structures in communities near the Palos Verdes Hills and resulted in 115 fatalities. Two major fault zones parallel the San Pedro Escarpment to

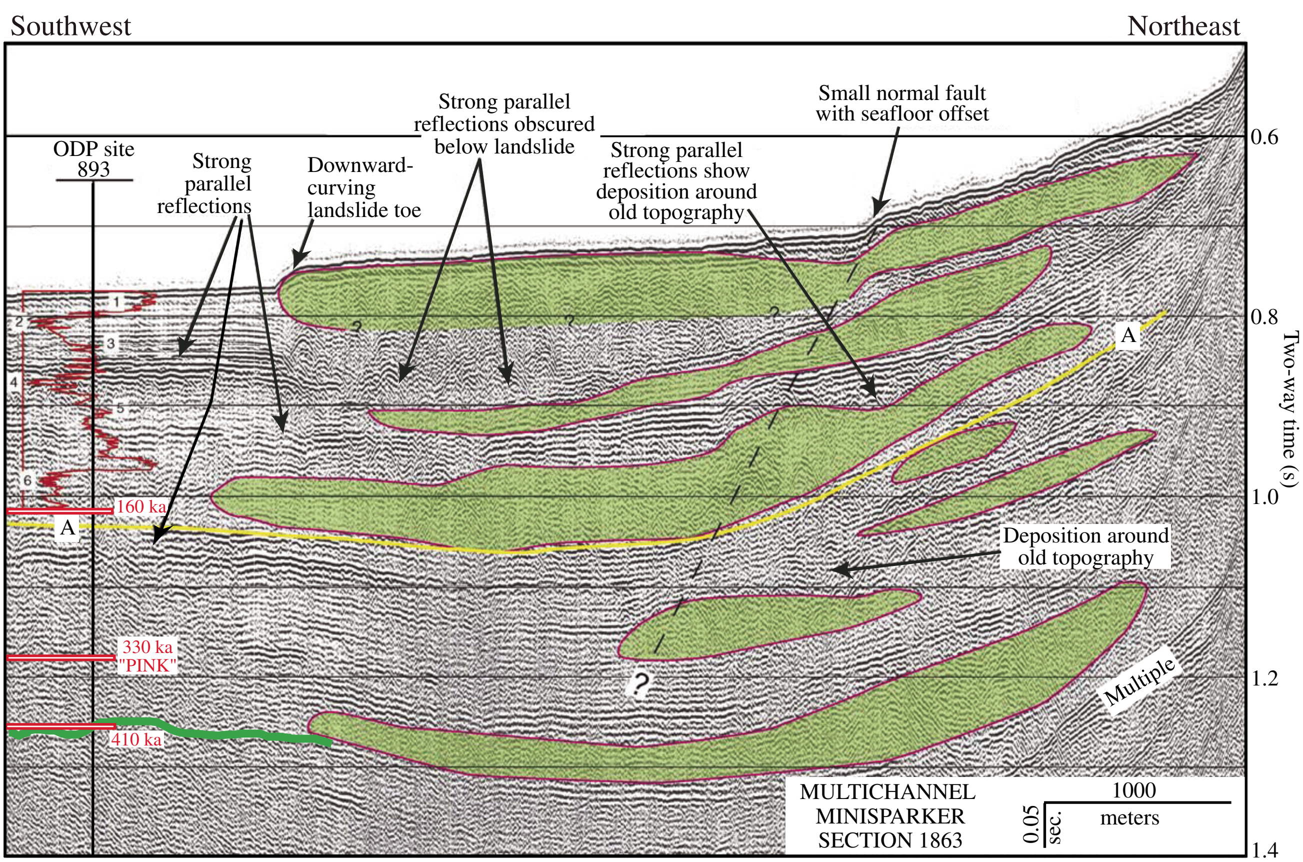

Figure 7. High-resolution, minisparker, seismic-reflection data showing landslide deposits (green shading) below the west lobe of the Goleta landslide complex (location shown in Fig. 4). The superimposed red curve shows oxygen-isotope data from Ocean Drilling Program (ODP) site 893; numbers along the curve show marine isotope stages (Kennett, 1995). The yellow line is “Horizon A” and represents rocks that are ca. 160 ka (after Fisher et al., 2005).

the northeast. The Palos Verdes Fault is only 10 km distant, and the Newport-Inglewood Fault, which produced the 1933 Long Beach earthquake, is 20 km away (see Fisher et al., 2004, for fault locations).

The existence of submarine landslide terrain immediately south of the Palos Verdes Peninsula and within the San Pedro Basin has been known for 50 years (Emery and Terry, 1956), but the extent and detailed morphology of the features was unknown until multibeam imagery recently became available (Gardner and Mayer, 1998; Gardner et al., 1999, 2002, 2003; Bohannon and Gardner, 2004). This imagery (Fig. 1A) shows a large variety of gullies cutting most of the 25-km-long San Pedro Escarpment with landslide deposits fringing its base. Two scars on the surface of the escarpment appear particularly fresh and not eroded (i.e., no gullies) and are identified as Palos Verdes landslide scars 1 and 2 (Fig. 1A). Blocky landslide debris (Figs. 1A and 8) that extends south from the base of the slope for ~10 km shows that landslides from the escarpment had considerable momentum when they reached the basin floor and that they did not fully mobilize into dispersed flows. Bohannon and Gardner (2004) estimated the volume of the void above landslide 1 scar to be between 0.34 and 0.72 km^3. Using radiocarbon dates from piston-core samples obtained near the distal toe of the landslide deposits, Normark et al. (2004) determined that the age of the Palos Verdes debris avalanche is ~7500 years old (also see Normark et al., this volume, Chapter 2.6, Fig. 6). Normark et al. (this volume, Chapter 2.6), however, speculate that there might have been several recent episodes of failure and that one of these might have been more recent than 7500 years ago.

Bohannon and Gardner (2004) used multichannel seismic-reflection data of the upper 600 m of basin fill to show that the more recent Palos Verdes debris avalanche deposits are underlain by numerous thick (~75 m), acoustically transparent lenses that are interpreted as ancient landslide debris (Fig. 9). Because there are no ODP borings in San Pedro Basin, ages are difficult to assign to these older deposits, although clearly, failures like the Palos Verdes debris avalanche have occurred repeatedly in the past. This conclusion is supported by the observation of a 10-km-wide section of the basin slope that is heavily gullied, as is common with old headwalls of landslides (Moore et al., 1989).

Given the extent of landslide features on the Palos Verdes margin, in combination with the tectonic setting and sediment forming steep slopes, a reoccurrence of large-scale slope failure at some time in the future seems likely. This fact presents a hazard of landslide-induced tsunamis, and these could impact both the nearby Ports of Los Angeles and Long Beach and adjacent coastal communities.

Other Failures on the Los Angeles Margin

In appraising the 120-km-long section of the Los Angeles continental margin mapped using multibeam imagery techniques (Gardner et al., 2002), one finds that most of the slopes are either smooth or somewhat gullied. Only limited parts of the margin show clear indications of slope failure on a scale that can be interpreted from a 1:140,000 map. One section that is dominated by both large and small failures is the San Pedro Escarpment, discussed above. The escarpment is the most consistently steep-slope area of the mainland part of the margin, outside of canyons (Lee et al., 2000). The eastern 10 km of this escarpment is occupied by the Palos Verdes debris avalanche, discussed above. The western part of the escarpment (termed the Redondo section by Bohannon and Gardner, 2004) contains only relatively shallow-seated landslides, although much of the slope is covered by them. Most of the lower part of this slope (water depths of 450 m to the basin floor of 600–800 m) is composed of landslide scars resulting from shallow-seated failures along roughly planar surfaces, perhaps a result of the influence of local stratigraphic units or paths of groundwater expulsion. The upper part of the slope contains several 0.5- to 1-km-wide amphitheaters that lie above deep gullies

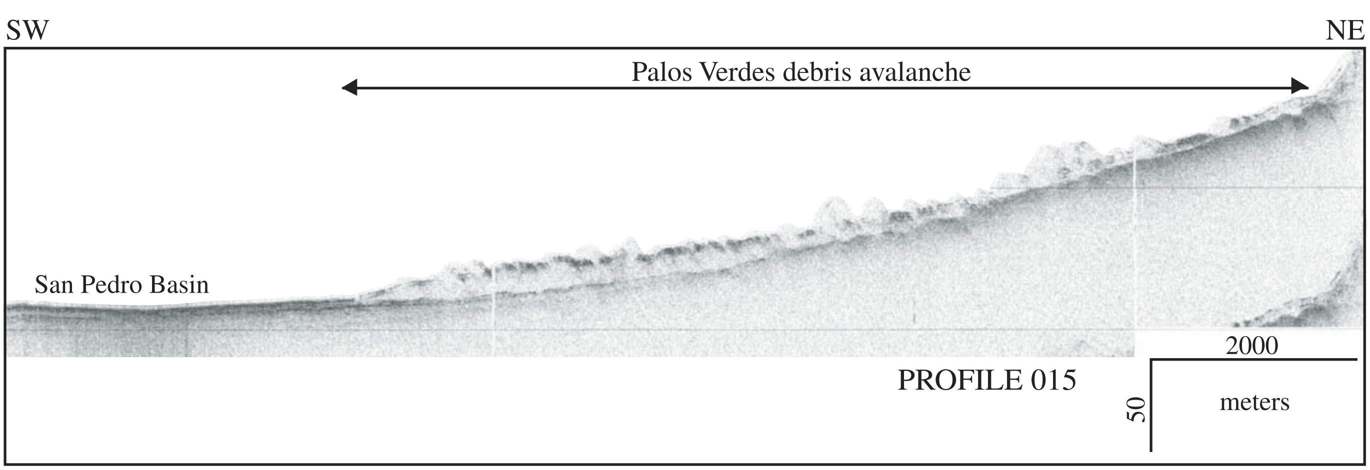

Figure 8. A profile of the blocky debris avalanche deposit extending south of the source region on the San Pedro Escarpment (see Fig. 1A for location).

(left part of Fig. 1A). These features are ambiguous and could relate to slope failure or erosion from gravity flows discharged near the shelf break. Gullies are ubiquitous along the margin, associated with or without amphitheaters or bowls near the shelf break.

Slope failures are also associated with submarine canyons. For example, Gardner et al. (2003) report mass wasting along both walls of Redondo Canyon and show several landslides that have blocked the channel in the upper reaches. These are similar to the numerous failures that have been mapped in the Sur and Ascension-Monterey Canyons by Greene et al. (2002), where landslides cause changes in the course of the channel (e.g., Sur and Monterey Canyons), undercutting the distal wall and leading to second generation failures (e.g., Ascension Canyon).

Slope failure is most intense in presently active canyons such as Redondo (Gardner et al., 2003) and one arm of Newport (Fig. 10). Other canyons, such as Santa Monica, San Gabriel, and several arms of Newport, head near the shelf break and do not extend to the present coastline. These canyons contain intricate and crosscutting channels, meanders, and cutoff meanders (Fig. 10). Some of these channel features have the appearance of landslide scars (e.g., scalloped sides of upper two arms of San Gabriel Canyon, Fig. 10) and may indeed be related to mass-wasting processes. However, some of the features must be related to hyperpycnal gravity flows, a result of river discharge with a density greater than that of sea water (Warrick and Milliman, 2003; Warrick and Farnsworth, this volume, Chapter 2.3).

Mainland Slope Failures Not Covered by Multibeam Imagery

Two significant gaps exist in multibeam coverage of the mainland slope (Fig. 3) of Southern California—the margins between Point Mugu and Point Dume (30 km) and between Dana Point and Cardiff (60 km). The first of these spans includes Hueneme and Mugu canyon-fan systems, and work is under way to complete mapping of this area. Debris flows have been identified and described in these fan system (Piper et al., 1999) and are not surprising given the size of the fans and level of activity.

The section of margin between Dana Point and Cardiff (Fig. 3) is complex, containing several small submarine canyons and

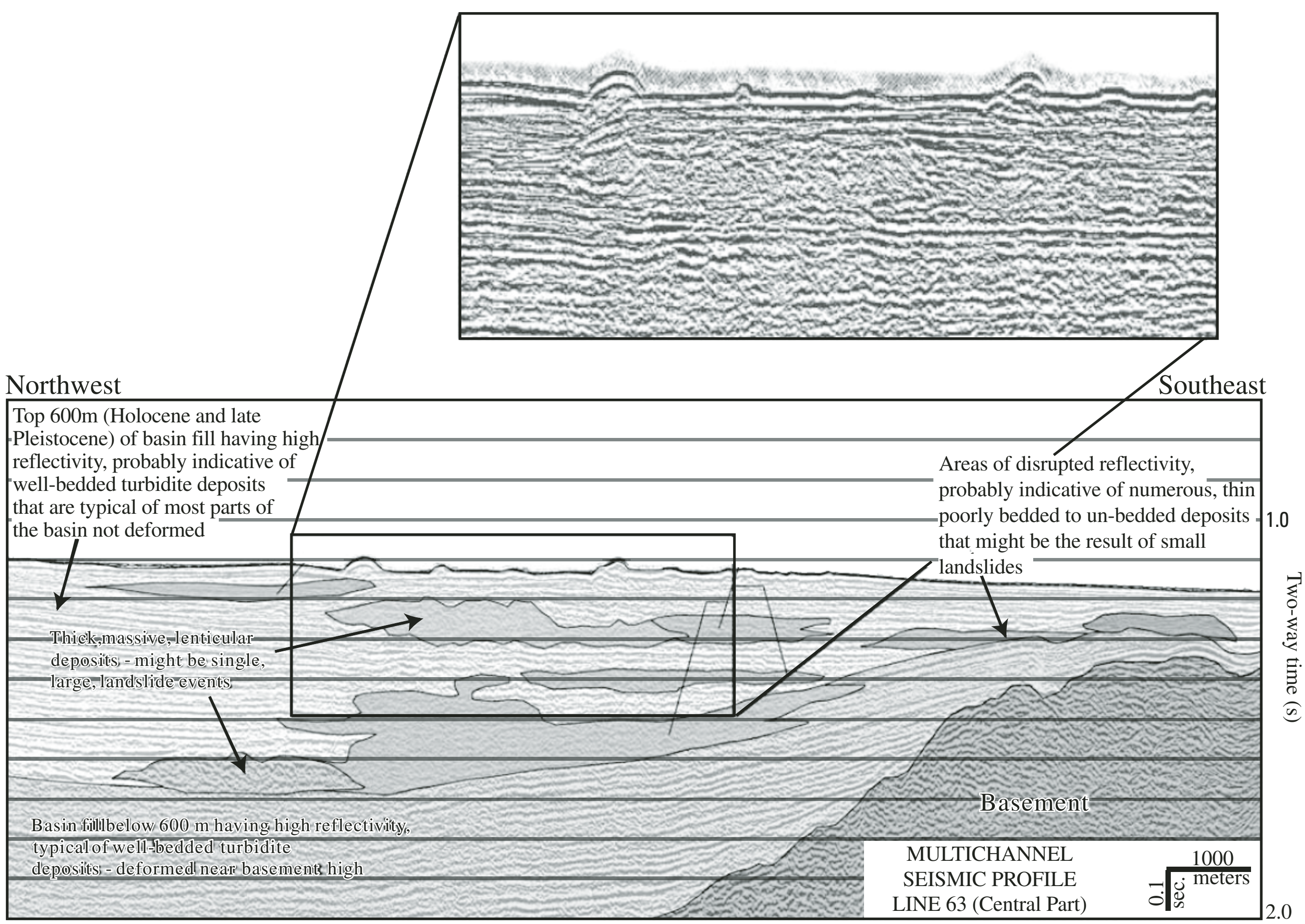

Figure 9. Segment of migrated, multichannel seismic profile showing lenticular deposits below the Palos Verdes debris avalanche that may indicate previous landslide events (after Bohannon and Gardner, 2004). See Figure 1A for location of profile.

many features that were identified as landslides during early studies of the area (Edwards et al., 1980; Richmond et al., 1981; Clarke et al., 1983). The area adjacent to San Mateo Point (Fig. 11A) was identified as containing perhaps the highest density of landslides (Edwards et al., 1980; example shown in Fig. 11B). However, recent bathymetry (Fig. 11A) shows a bulge in the basin margin but not clearly defined landslide features such as those in Santa Barbara Channel and along the San Pedro Escarpment. Also, nearby multichannel profiles (Fig. 11C) illustrate that much of the bulge is a result of faulting associated with the San Mateo thrust (Ryan et al., this volume) rather than landslides. Accordingly, the original interpretations of large areas of mass wasting are likely exaggerated. Rather, there are probably several small, shallow-seated slides (e.g., Fig. 11B) that lie atop a region of tectonic folding and thrusting (Fig. 11C; Ryan et al., this volume).

Sediment Mass Failures near Islands and Banks

The bathymetric relief around offshore islands and banks is great, and in many cases the relief is the morphologic expression of offshore faults. In early regional work (as summarized in Fig. 2), the slopes surrounding Santa Cruz Basin were identified as containing a particularly large number of failures (Nardin et al., 1979; Field and Richmond, 1980). Such an increased density of mapped failures could result from the large range in water depths of the slopes (over 1500 m), relatively high sediment accumulation owing to proximity to the mouth of the Santa Clara River, or

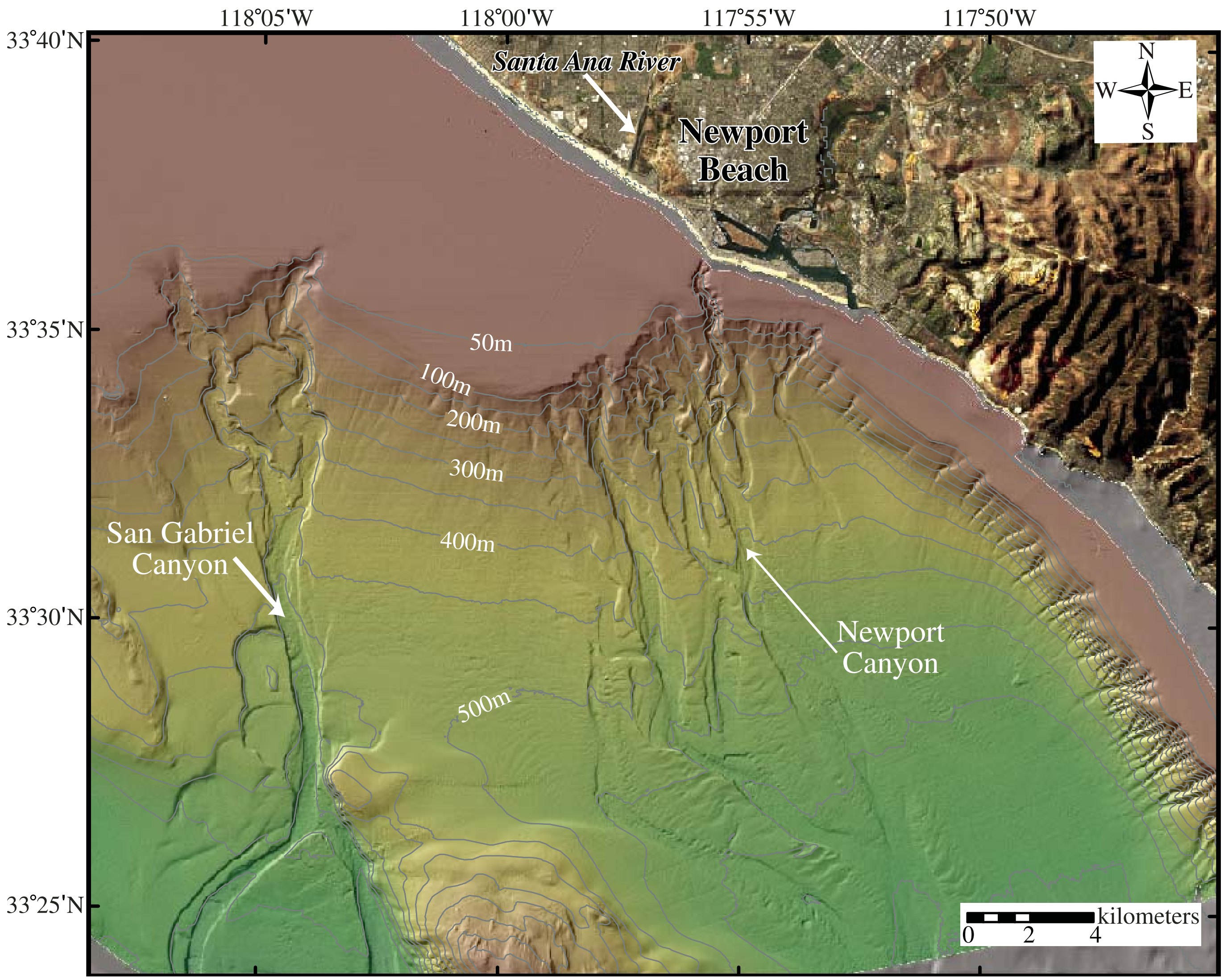

Figure 10. Multibeam image showing the heads of San Gabriel and Newport Canyons. The image shows that canyon heads (sources of gravity flows) have migrated over sections of the shelf break within both canyon systems. Some of the features within the multiple channels (e.g., scalloped scarps near shelf break and along sides of channels) could be related to landslide events, but others may be related to hyperpycnal flows from local rivers, in particular, the Santa Ana River (part of image given by Gardner et al., 2002).

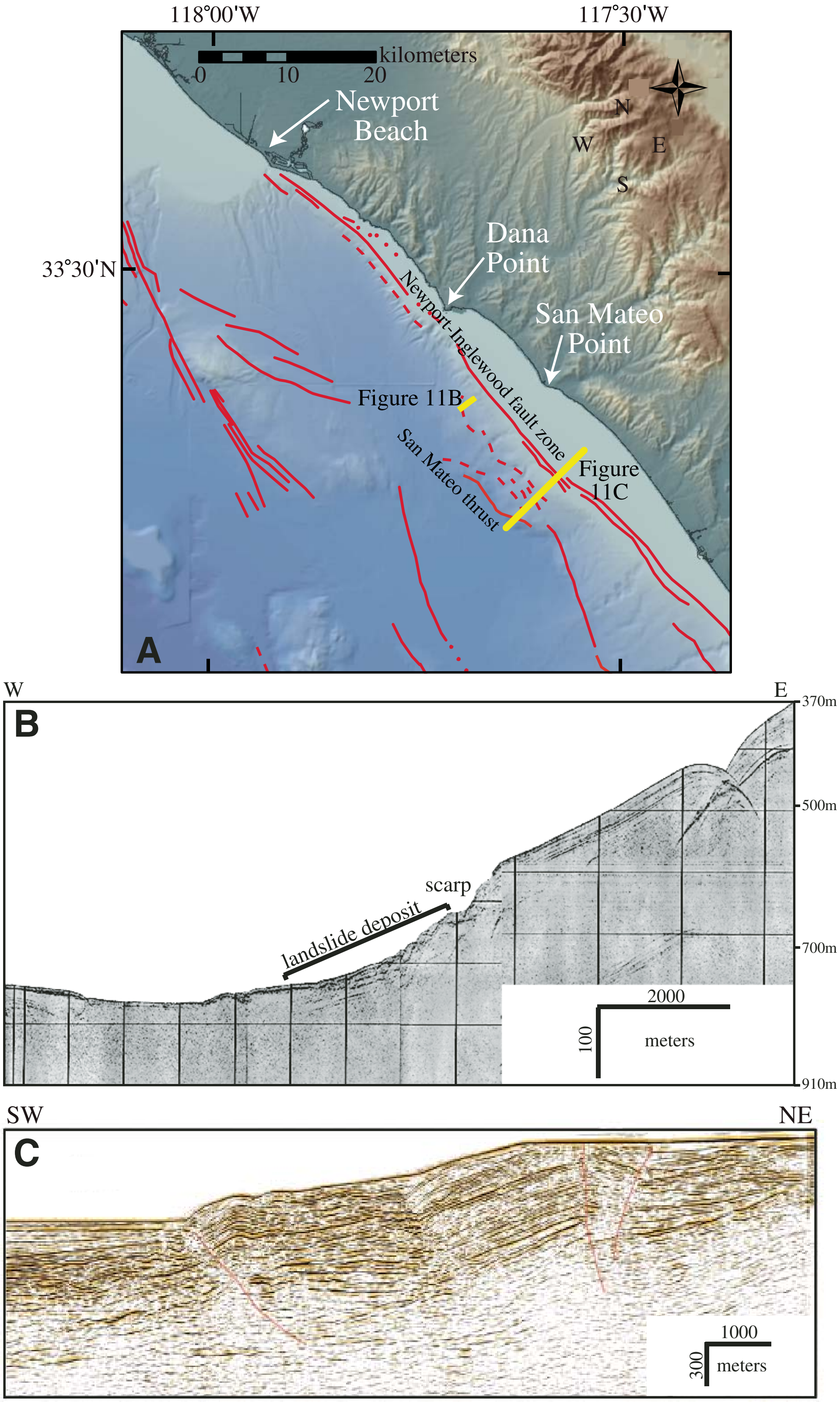

Figure 11. The San Mateo thrust, an area thought in early studies to include a variety of landslide deposits. (A) The area between Newport Canyon and San Mateo Point based on best available bathymetry. (B) A shallow-seated landslide deposit off San Mateo Point reported by Edwards et al. (1980). (C) The general pattern of folding and thrusting, without significant landslides, characteristic of this section of margin (migrated multichannel data from Western Geophysics). Faint red lines identify interpreted faults.

more intense effort expended mapping the area because of anticipated oil and gas lease sales. Other areas with high densities of landslides include the sides of Cortes Ridge and Bank and the sides of San Nicholas Basin (Fig. 2). Ages of failures in the outer basins and banks are unknown so the risk of future landslides cannot be assessed.

Legg and Kamerling (2003) described two large, basement-involved landslide features west of San Diego, one on the northeast-facing Thirtymile Bank escarpment and the other along the southwest side of Fortymile Bank (locations on Fig. 3). The volumes of the two failure masses exceed 1 km^3 for the Thirtymile Bank landslide and 5–10 km^3 for the Fortymile Bank failure. Whether the failures occurred as two individual events involving these full volumes of material in two rapid motions or if each resulted from multiple motions, perhaps each involving only parts of the overall failure features, is unknown. Legg and Kamerling (2003) estimated that the age of the Thirtymile Bank failure is "old," perhaps Miocene to Pliocene (>2 Ma). The Fortymile Bank failure is thought to be younger (late Pleistocene, <1 Ma). Either failure, if it occurred as one single motion of the total volume of material, was likely tsunamigenic, as any future failures of similar scale would be.

TSUNAMI POTENTIAL

Efforts have been made to estimate the size of tsunamis that would have resulted from the largest observed failure complexes in Southern California (Borrero et al., 2001, 2004; Legg and Kamerling, 2003; Bohannon and Gardner, 2004; Locat et al., 2004; Greene et al., 2006). Both Borrero et al. (2001) and Greene et al. (2006) generated numerical models of tsunami waves that may have resulted from the Goleta slide. Borrero et al. (2001) assumed that all three major lobes moved at once to estimate peak tsunami runup of up to 20 m with significant waves extending along an 80-km-long stretch of the northern shore of the Santa Barbara Channel. Greene et al. (2006) assumed a less severe scenario in which the lobes failed at different times (although still one in which all components of an individual lobe failed as part of one event). Their modeling showed that the most recent failure of Goleta slide would produce runup as great as 10 m along an ~30 km long stretch of coast, mostly west of Goleta and Coal Oil Points.

Locat et al. (2004) developed a simplified model for the motion of Palos Verdes Landside 1, relying upon available geometric and physical properties information. In addition to showing that the failure was likely caused by an earthquake, this model showed that the initial velocity of the landslide may have exceeded 40 m/s and that most of the event was completed within 5 min. Applying Murty's (1979) tsunami model, Locat et al. (2004) estimated that the landslide likely produced at least an 8-m-high tsunami at its source, depending upon several poorly constrained input parameters. The tsunami height decreases with distance from the source area as a result of radial spreading and then increases as the tsunami shoals toward shore. Bohannon and Gardner (2004) also used a simplified analysis of a failure of the most recent part of the landslide complex to estimate an initial wave height of 8–12 m. Borrero et al. (2004) used somewhat different techniques to estimate runup of 5.5 m along the steep cliffs of the Palos Verdes Peninsula and up to 3 m for heavily developed areas along the coast extending 30 km to the east. For the Fortymile Bank failure presented by Legg and Kamerling (2003), the authors estimate a maximum tsunami height of 7–9 m for a rotational slump model and a height of ~50 m for a translational slide model.

CAUSES OF FAILURE

The discussion above shows that there are many landslides interpreted to be distributed along the slopes of the Southern California Borderland. However, with the possible exception of some relatively old, large failures on offshore banks discussed by Legg and Kamerling (2003), most of the failures presented are small to medium in size (i.e., <0.1 km^3) and likely incapable of generating significant tsunamis. The Goleta slide in the Santa Barbara Channel and the Palos Verdes debris avalanche off Los Angeles are the only two major landslide complexes that are clearly large enough to have generated tsunamis and also show repeated motions at the same location. One would expect that perhaps unique sets of environmental conditions cause these locations to behave differently from the rest of the Borderland.

Greene et al. (2006) listed four major mechanisms for causing failure in the Southern California Borderland—sediment accumulation, fluid flow, tectonic oversteepening, and seismic excitation. Tectonic oversteepening can be particularly acute in areas near faults and anticlines, as suggested by Fisher et al. (2005). Virtually the entire inner Borderland is seismically active (Legg and Kamerling, 2003), and many of the failures are thought to have been triggered by seismic loading (Edwards et al., 1980; Lee and Edwards, 1986; Locat et al., 2004; Fisher et al., 2005; Greene et al., 2006). However, because of the ubiquitous nature of earthquakes in the inner California Borderland area, seismic loading does not explain why there are only two locations with large repeated failures. Therefore, other factors must precondition these slopes for failure so that at some point one of the plentiful, expected earthquakes triggers the event.

In the case of the Goleta slide, the other three mechanisms for causing failure (in addition to seismic loading) are present, and the tendency of this section of margin to fail may be related to the mechanisms combining in their influence. For example, Greene et al. (2006) point out that 90% of sediment input into the Santa Barbara Channel originates from the Ventura and Santa Clara Rivers, which produce a point source in the northeast corner of the channel. Fisher et al. (2005) suggest that much of this sediment is deposited in a shelf-edge delta at the head of Goleta slide and that this is the material that fails periodically. In the same general area, and perhaps producing accommodation space for deposition of the delta, are a set of faults and anticlines with particularly intense seismic activity directed toward oversteepening the deltaic deposits (Fisher et al., 2005). Finally, the area is strongly impacted by fluid flow (Greene et al., 2006) including the hydrocarbons that make the channel a major oil-producing area. Many active seeps, mud volcanoes, and bacterial mats have been observed with remotely operated vehicles and submersibles, indicating continuing fluid flow. The fluid flows are likely directed and focused along faulted anticlines (Greene et al., 2006). The result is a situation in which a deltaic deposit forms as a result of significant sedimentation. The deposit in turn is influenced by fluid pressures and oversteepening; therefore, periodically it fails catastrophically under the influence of one of the many earthquakes. The recurrence interval of failure is likely determined by sedimentation processes forming a critically large deposit of conditioned sediment. Earthquakes are frequent enough that they are not likely the limiting factor. This process must be influenced in a presently poorly understood way by a mix of changes in the local sea level, sediment supply, and tectonic and other geologic controls.

The Palos Verdes debris avalanche occurs on one of the steepest slopes in the Los Angeles offshore region (Lee et al., 2000). The steepness contributes not only to the occurrence of the large debris avalanche, but also to the occurrence of many other smaller shallow-seated failures. In addition to steepness, a critical factor influencing this slope is the likely presence of high, excess fluid pressures, which are suggested by the presence of hot-fluid seeps on the shelf immediately landward from the headwall of the landslide (Hampton et al., 2002). It is not presently known whether the recurrence of large failures offshore of the Palos Verdes Peninsula is determined by reloading of the failure zone by continued sedimentation or by migration of the zone of failure within the San Pedro Sea Valley. This latter interpretation is supported by the large area of highly gullied terrain (Fig. 1A). High sedimentation rates in the former explanation derive from sediment supplied by the Los Angeles, San Gabriel, and Santa Ana Rivers. Predicting future failures of the San Pedro Escarpment will require a better understanding of these processes.

The plentiful other landslides mapped throughout the Borderland must also be determined by a combination of conditioning factors. However, they seem to be more randomly distributed and could perhaps relate most strongly to the particular distribution of shaking intensity from a single earthquake.

FAILURE MORPHOLOGIES

The landslides discussed in this chapter display a variety of morphologies ranging from relatively small, shallow-seated, limited-runout sediment flows in Santa Barbara Basin (Gaviota mudflow, Conception fan slide, and east slides 1 and 2; Fig. 4), to similarly small, somewhat greater runout, sediment failures along the western section of the San Pedro Escarpment (Fig. 1A), to large-scale and deep-seated slope failure complexes—the Goleta slide (Fig. 4) and Palos Verdes debris avalanche (Fig. 1A). The large-scale failure complexes in turn display different surface morphologies. The Goleta slide consists of three large lobes with relatively smooth surfaces (Fig. 4), whereas the Palos Verdes debris avalanche is more of a blocky debris field, which is still somewhat lobate in form.

The morphology of the landslides likely relates to the nature and density state of the source material. The smaller, shallow-seated failures do not show much blockiness and apparently consist of unlithified, relatively recently deposited sediment. The mobility of these sediment failures (relative runout) may relate to the density state of the sediment on the slope before failure. As discussed by Lee et al. (1992), sediment that has a lower density than a baseline "steady-state" condition tends to contract and lose strength during failure. The lower the density, the greater will be the loss of strength. The mobility of the flows then is likely a function of the density at which the recently deposited sediment was emplaced (in turn a function of current activity, sediment grain size, and mineralogy).

The morphology of the smooth-surfaced, lobate Goleta slide may also indicate that the source material for the failures was unlithified sediment, as contrasted with the blocky surface of the Palos Verdes debris avalanche, which more clearly points to bedrock as a source. One could make the case that the Goleta slide originates as a shelf-edge delta that is periodically deposited in the scar of earlier episodes of failure (Fisher et al., 2005). The material in the delta would be relatively young, rapidly deposited and loose, an excellent combination for a mobile sediment failure. Partly arguing against an unlithified sediment failure as the source of the Goleta slide, however, is the appearance of blockiness (Fig. 6) in the buried landslide deposits. In fact, the buried blocky surface at Goleta seems almost as rough as that of the Palos Verdes debris avalanche (Fig. 8). Note that the rate of sediment accumulation since the occurrence of both failures is much greater at Goleta (~1.45 m/k.y., as discussed previously) than at Palos Verdes (~0.4 m/k.y., Normark et al., 2004). Given that the landslides have similar ages, as discussed above, one would expect that the Goleta slide would be buried more deeply and that the post-failure sediment accumulation would give the seafloor a smoother surface. Accordingly, both failures may involve some lithified rock that assumed a moderate degree of mobility during failure. The resulting surface morphology is created in part by subsequent sediment accumulation.

CONCLUSIONS

Thirty years of surveys have shown that the slopes of the Southern California Borderland contain a large number of landslide deposits. As technology has improved from inference between seismic-reflection profile lines toward multibeam imagery, our knowledge of the locations and extent of landsliding has matured. We now recognize that general distribution maps based on these profile lines, such as shown in Figure 2, provide a picture of the scale of activity but are likely inadequate in terms of the details of the geometries of the failures. New multibeam images show these details much more effectively. These images show that there are numerous small landslide features, with lateral dimensions less than ~2 km, and that these are preferentially located on the north side of the Santa Barbara Basin and on the San Pedro Escarpment. Outside of the areas mapped with multibeam, there are likely many other landslides of this scale whose discovery awaits this type of rigorous mapping.

There are only two large landslide complexes on the mainland slope—the Goleta slide and the Palos Verdes debris avalanche. Both of these submarine landslides indicate repeated recurrences of catastrophic slope failure and have an associated risk of tsunami generation. Recurrence intervals are not well constrained, but we speculate that individual large failures within the Goleta slide complex occur about every 15 k.y. The most recent large failure of the Palos Verdes complex is 7500 years old, although a younger, smaller failure may have occurred. Accordingly, the order of magnitude for the recurrence interval of failure on one of these two large complexes is between 5000 and 10,000 years.

The youngest failure with an age estimate is the Gaviota mudflow, and it is much younger than the large complexes. Its age is within a few hundred years of present and thus may have occurred during the 1812 Santa Barbara Channel earthquake.

If a sediment mass failure were to occur in the future associated with one of the large landslide complexes, it would likely generate a damaging tsunami. Although input parameters for tsunami modeling are difficult to define accurately, tsunamis from a failure of one of the lobes of the Goleta slide would likely have subaerial runups on the order of 10 m over a 30-km-long stretch of coast. Similarly the Palos Verdes debris avalanche would likely have a runup of up to 3 m over a 30-km-long stretch of developed, low-lying coastline extending eastward from the entrance to Los Angeles Harbor.

Most landslides within the Southern California Borderland are likely triggered by earthquakes. The locations of smaller landslides may be determined by their proximity to areas of maximum shaking. The larger features likely occur at locations that have been conditioned for failure by other processes. In the case of the Goleta slide, the environment was conditioned by deposition of a shelf-edge delta that resulted from large sediment inputs from local rivers. The environment was further conditioned by proximity to faults and anticlines and the injection of high fluid pressures. In the case of the Palos Verdes debris avalanche, one clear conditioning factor was the presence of a steep slope generated by the same folding process that produced the Palos Verdes Hills. In addition, the environment appears to be influenced by high fluid pressures suggested by numerous hot seeps on the adjacent continental shelf.

Smaller failures appear to involve recent sediment deposits that mobilized and flowed out of the source region. The mobility of the flows likely relates to the relative density state of the source material. The two large landslide complexes each consist of blocky material that may relate to a bedrock source. The Goleta slide has a smoother surface either because it originated from a sediment-rich, shelf-edge delta failure or because it is more deeply buried by subsequent sediment accumulation.

ACKNOWLEDGMENTS

The authors acknowledge support from the U.S. Geological Survey, the David and Lucile Packard Foundation through the Monterey Bay Aquarium Research Institute, and the Office of Naval Research. This manuscript benefited greatly from helpful reviews by David Twichell and David Mosher. We particularly acknowledge the contributions to this work by our late colleague, William Normark.

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Manuscript Accepted by the Society 5 November 2008