TYPES AND MECHANISMS OF MASS-WASTING EVENTS THAT SHAPE THE CALIFORNIA CONTINENTAL MARGIN, USA

H. Gary Greene, Monterey Bay Aquarium Research Institute and Moss Landing Marine Laboratories, Moss Landing California
Lee Y. Murai, Moss Landing Marine Laboratories, Moss Landing, California
Steven N. Ward, University of California, Santa Cruz, California
Michael A. Fisher, U.S. Geological Survey, Menlo Park, California
Charlie E. Paull, Monterey Bay Aquarium Research Institute, Moss Landing, California
Homa J. Lee and William R. Normark, U.S. Geological Survey, Menlo Park, California
Norman A. Maher, AOA Geophysics, Inc., Moss Landing, California

ABSTRACT

Multibeam bathymetric and seismic reflection profile data collected along selected parts of the California continental margin indicate that mass wasting is a significant process that has shaped the seafloor in the past and is presently active today. A variety of mass movement features mapped along the margin indicate that many different triggering mechanisms are at work to produce landslides. Some of these mass-wasting features cover extensive areas such as the 130 km^2 Goleta landslide in the Santa Barbara Basin a complex compound slide that has been produced from different types of movements and mechanisms occurring at different times throughout its failure history. Potential triggering mechanisms for submarine landslides include fluid flow, tectonic oversteepening of slopes, earthquakes, sediment and rock undercutting in submarine canyons, sediment accumulations reaching the angle of repose, and terrestrial input from subarial mass-movement features. Many of these slides appear capable of producing a tsunami.

RÉSUIMÉ

L'obtention de levés sismiques et de données bathymétriques à partir de levés multifaisceaux de quelques secteurs de la marge continentale californienne révèle que l'érosion en masse est un processus qui a formé les fonds marins tant par le passé et qu'aujourd'hui. Les diverses formes associées à des mouvements de masse, qui ont été cartographîées le long de la marge, suggèrent que plusieurs mécanismes déclencheurs sont actifs pour produire les glissements de terrain observés. Certaines de ces formes d'érosion en masse couvrent des étendues aussi grande que 130 km^2. Le glissement de Goleta, dans la bassin de Santa Barbara, est un glissement complexe et composite qui résulte de divers types de mouvements de terrain et de mécanismes de ruptures qui sont survenus à diverses périodes de son histoire. Les mécanismes déclencheurs possibles de tels glissements sous-marins incluent l'écoulement souterrain, l'accentuation tectonique des pentes, les séismes, l'affouillement en pied de talus des roches et des sédiments dans les canyons sous-marins, l'accumulation des sédiments à des angles proches des valeurs d'équilibre, et des apports terrestres de glissements sub-aériens. Plusieurs de ces types de mouvements sont capables de produire des tsunamis.

1. INTRODUCTION

The California continental margin is heavily incised with canyons and gullies and contains extensive submarine landslide scars. The types of submarine failures that have been mapped along the California continental margin include thin sediment or mud flows, debris flows, down-dropped blocks and rotational slumps, rock falls and rock debris avalanches, and complex compound mass movement features (Greene et al., 2002; Echhubl et al., 2002; Bohannon and Gardner, 2004). These failures are found at all depths along the margin, ranging from those in less than 100 m water depth within the heads of submarine canyons to others located along the base of the continental slope at depths approaching 3500 m (Gutmacker and Normark, 1993; Greene et al, 2002). In addition, trans-terrestrial slides occur along the steep coasts and narrow shelf areas such as along the western margin of the Santa Lucia Mountains (Big Sur coastline) where modern subaerial inputs contribute to ongoing submarine mass- movements.

2. STUDY AREAS

We have selected three sites (Central California/Monterey Bay, Santa Barbara Channel, and Southern California/Long Beach) along the California continental margin to compare in our study of submarine mass-wasting (Fig. 1). All three sites lie in areas of extensive faulting with active earthquakes. The objective of this paper is to describe and illustrate the various types of landslides that exist along the California margin.

Our intent is to provide developing concepts on how these various mass-wasting features were formed and evolved through time to be used as “food-for-thought” and discussion. Concepts presented here have not been fully developed as the length and format of this publication prevents this from happening.

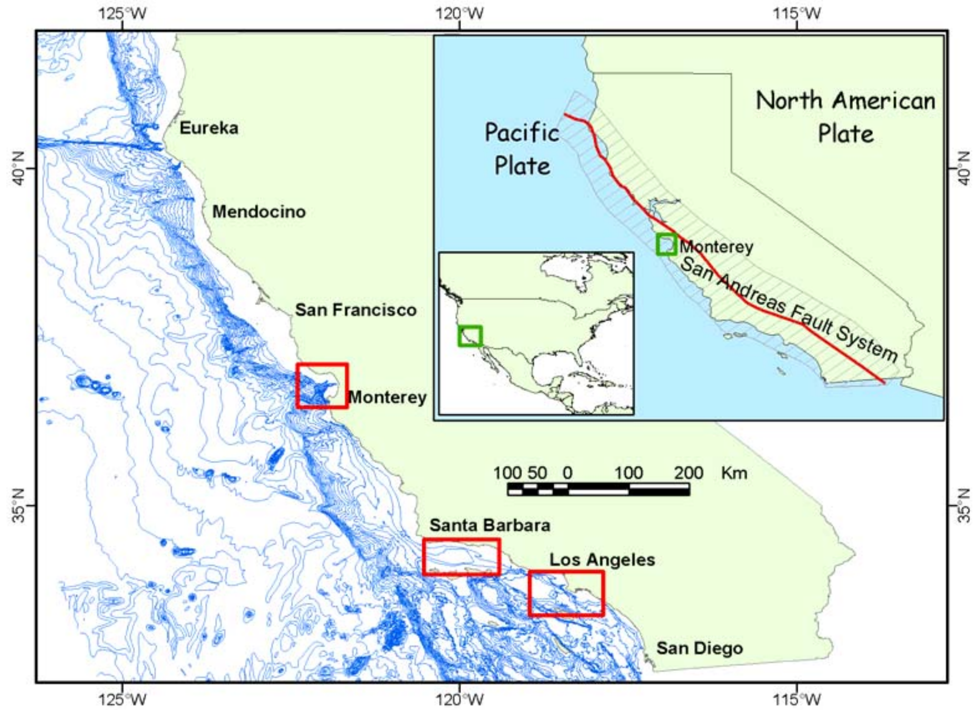

Figure 1. Index map of California continental margin showing the three study sites.

2.1. Central California – Monterey Bay Region

High-resolution EM300 30 kHz multibeam bathymetry and backscatter data collected by the Monterey Bay Aquarium Research Institute (MBARI) show that the central California offshore morphology is dominated with mass wasting features such as canyons, gullies and landslides including thin sediment flows, rotational slumps, and debris flows (Greene et al., 2002). The Monterey Bay region is cut with many faults that are part of the San Andreas fault system (Greene et al., 1973; Greene, 1990; Greene and Ward, 2003). Two major seismically active northwest-southeast-trending conjugate fault zones, the Monterey Bay and Palo Colorado-San Gregorio fault zones, slice through Monterey Bay (Cockerham et al., 1990; Fig. 2). Extensive mass-wasting scars occur where the faults cross the canyon, suggesting that the deformation produced by movement along these fault zones has weakened the rocks exposed in the canyon's walls (i.e., the Monterey Meander). Recent and historical mass-movement events have occurred in the headward part of the canyon as shown by subtle less pronounced mature or older geomorphic features along the upper walls (Older Slump in Fig. 3) and shelf areas and by fresh, youthful geomorphic features along the base of the canyon walls (Monterey Canyon Head Slump in Fig. 3). A small slump occurred along the southern head wall of Monterey Canyon during the 1989 Loma Prieta Earthquake causing a small tsunami (Schwing, et al., 1990).

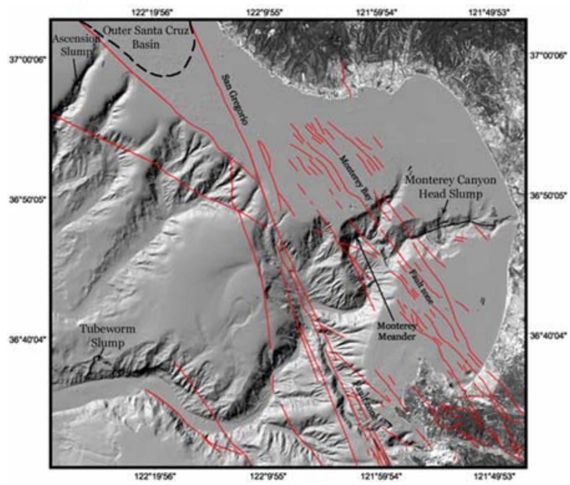

Figure 2. Fault traces overlaid upon MBARI EM300 30kHz multibeam bathymetry that shows the extensive amount of mass wasting taking place in the Monterey Bay region. Major mass-movement features and location of the Outer Santa Cruz hydrocarbon basin noted. Modified after Greene and Ward (2003).

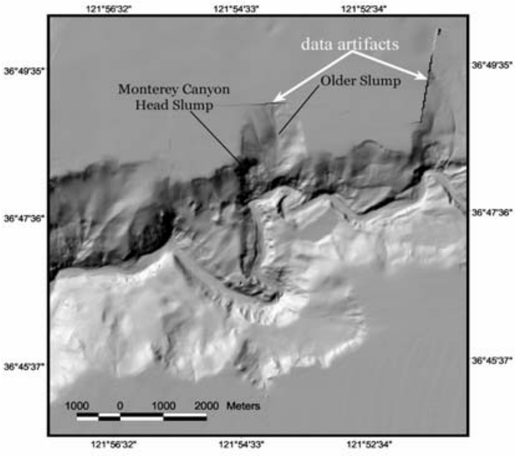

Figure 3. MBARI EM300 30 kHz multibeam bathymetric image showing the modern day Monterey Canyon head slump, a retrogressive slump resulting from canyon wall undercutting, and the Older slump that cuts into the Aromas aquifer and may have failed at a time of lower sea level when fresh water flowed from the aquifer. Modified after Greene and Ward (2003).

Slump blocks located in many of the canyons of central California sometime occur in pairs with an accompanying failure, or mimicking slide, located across the canyon axis, on the opposite wall of the canyon from the main slump (i.e. Ascension slump in Ascension Canyon in Fig. 4 and as described for Sur Canyon by Greene et al., 2002). In addition, the heads of Ascension and Año Nuevo Canyon have collapsed heads or down-dropped mass-movement features in their heads. Similar types of features have been investigated by us offshore of Point Conception and suggest that the heads of quite a few canyons along the California margin may have formed from mass-wasting.

Subaerial landslides are prominent along the Big Sur coast located south of Monterey Bay. Here landslides occur on a regular basis (yearly) especially during times of high rainfall (El Nino events) and mass-wasting sheds terrestrially eroded material into the marine environment.

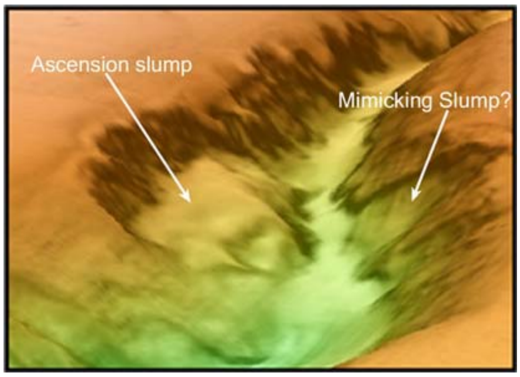

Figure 4. Oblique view of Ascension slump located in Ascension Canyon showing offset canyon axis and mimicking slump that may have resulted from pushing the canyon’s axis over to the adjacent wall where undercutting took place. Image produced from MBARI EM300 30 kHz multibeam bathymetery data.

2.2. Santa Barbara Channel

The Santa Barbara Channel located north of the Southern California Borderland is a compressional tectonic regime where considerable east-west-trending thrust faults and folds occur (Yerkes et al., 1981; Vedder et al., 1989; Eichhubl et al., 2002; Fig. 5). High resolution EM300 30 kHz multibeam bathymetry collected by MBARI show that the northern flank of the Santa Barbara Basin has the highest concentration of mass wasting features of the area (Fig. 6). The large 130 km^2 Goleta slide, a complex

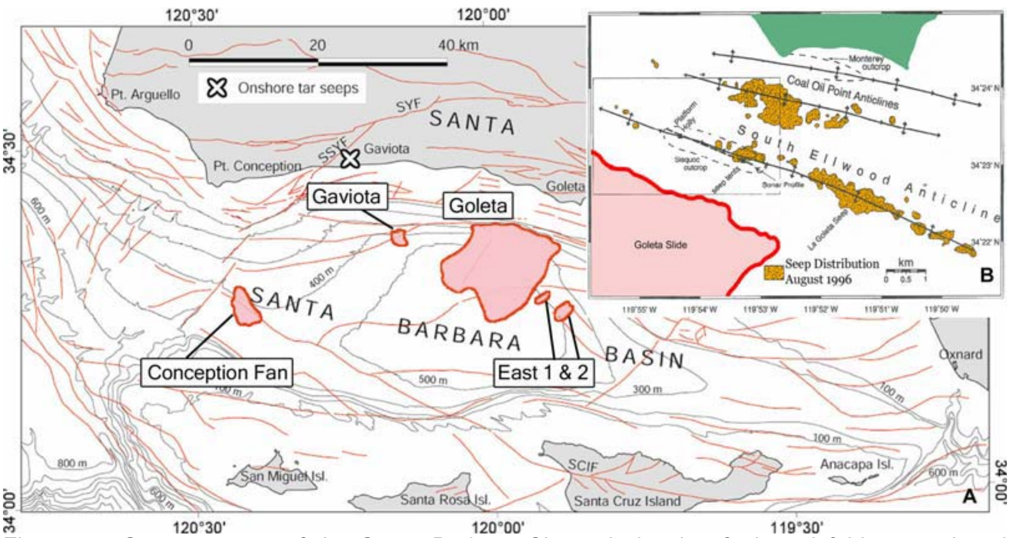

Figure 5. Structure map of the Santa Barbara Channel showing fault and fold traces in relationship to submarine landslides. A) Fault traces and landslides. Modified from Yerkes et al. (1981). B) Folds and distribution of seeps in relationship to head scarp of Goleta slide. Modified after Quigley et al. (1999).

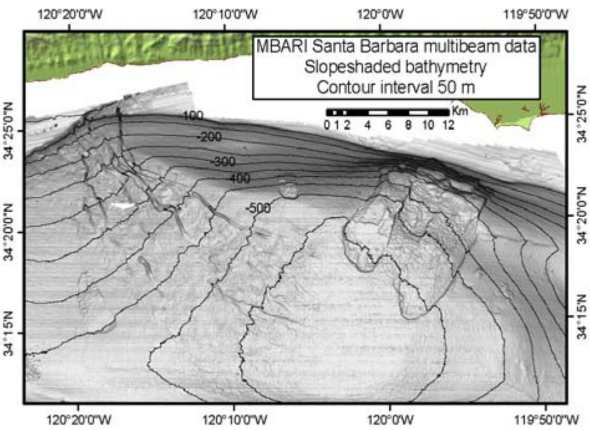

Figure 6. MBARI EM300 30 kHz multibeam bathymetry image showing submarine landslides along the northern flank of the Santa Barbara Basin.

compound slide that represents multiple failure events heads at the continental shelf break, adjacent to a major fault and fold zone and hydrocarbon basin called the Ellwood trend (Echhubl et al., 2002; Figs. 5 and 7). This is an area of considerable oil and gas seeps that trend along structure. Multi-channel seismic reflection profiles collected across the Goleta slump by the USGS show that there are several buried landslide deposits beneath the Santa Barbara Basin floor and buried slump blocks near the base of the steep northern slope (Fig. 7A). Extrapolation of the sedimentation rates of Thorton (1984) suggest that the 52.9 m of mud sediment cover over the head slump block of the eastern lobe on the Goleta slide took between 21.2 and 30.6 Ka to accumulate (Fig. 7B).

Several other failures exist along the northern Santa Barbara Channel, which are located near the base of the slope between 400 m and 450 m water depth (Fig. 6). These slides exhibit cracks that appear to be propagating laterally along the slope from beneath their head scars and near the boundary between areas of excavation and accumulation (Echhubl et al., 2002; Figs. 6 and 7). The Gaviota slide (Edwards et al., 1995) west of the Goleta slide has the most prominent crack of all of the slides, which laterally extends across the slope in an easterly direction for over 7 km, nearly connecting with the head scar of the western lobe of the Goleta slide (Fig. 8).

2.3. Southern California – Long Beach

A mosaic of High resolution multibeam bathymetry data (using EM300 30 kHz, EM1000 95 kHz, EM3000 300 kHz systems) collected along the Santa Monica Bay and San Pedro-Long Beach shelf show extensive gullies, canyons, and areas of mass movement (Gardner and Dartnell, 2002; Gardner et al., 2003; Dartnell et al., 2004; Fig. 9). This area is also heavily cut by faults with two major right-lateral strike-slip fault zones (Palos Verdes and Santa Monica Bay fault

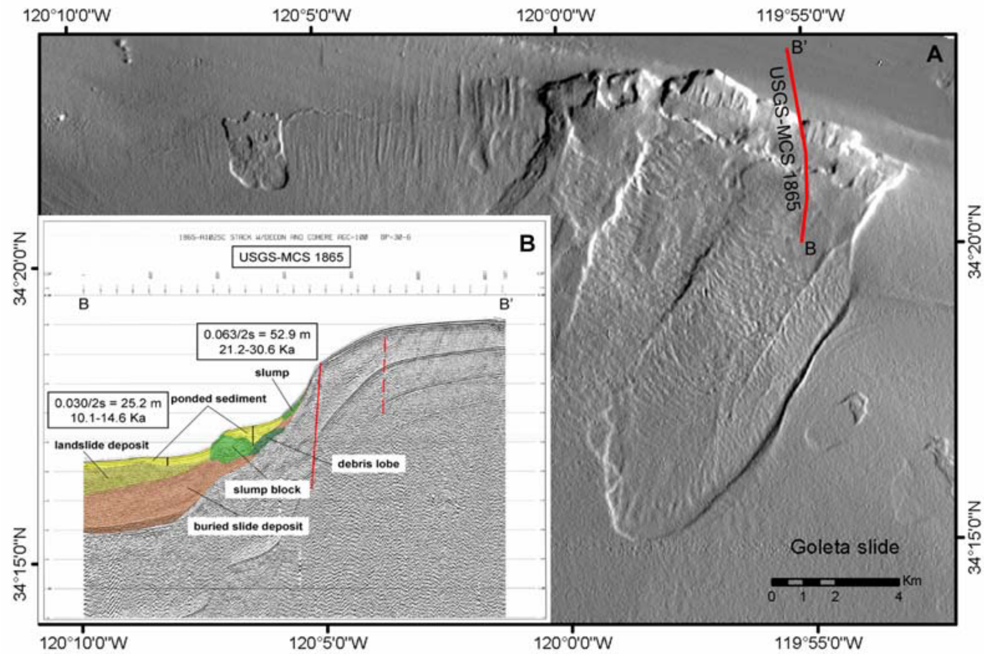

Figure 7. Multichannel seismic reflection profile collected across the head scarp of the eastern lobe of the Goleta slide by the USGS showing buried slump block. A) Location of seismic reflection profile. B) Seismic reflection profile with age of sediment covering slump debris based on sediment thickness and a sediment accumulation rate of 173 cm/ka to 250 cm/ka calculated by Thorton (1984), Edwards et al. (1995), and Eichhubl et al. (2002).

zones) that deform the shelf and slope along this margin (Vedder et al., 1986; Yerkes et al., 1981; Legg, 1986). A large (nearly 100 km^2 area of excavation and accumulation) submarine rock debris avalanche is clearly seen in the multibeam image offshore of the Palos Verdes Peninsula (Lee et al., 2003, 2004; Bohannan and Gardner, 2004; Normark et al., 2004; Fig 9).

This feature heads at the shelf break west of the major strand of the seismically active Palos Verdes fault zone and the Signal Hill hydrocarbon reservoir (Fig. 9A). The heavily gullied head scar of this landslide exposes Miocene Monterey Formation rocks (a hydrocarbon source and reservoir rock) and younger Pliocene and Pleistocene sedimentary rocks (Vedder et al., 1986). The debris flow extends nearly 10 km from the base of the head scar and is distributed over an area of ~60 km^2 (Fig. 9B).

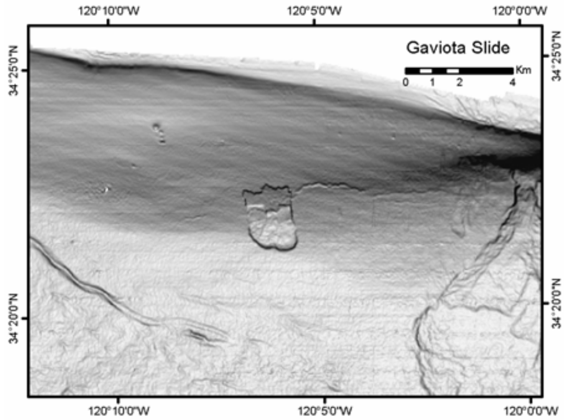

Figure 8. MBARI EM300 30 kHz multibeam bathymetry image of the Gaviota slide and associated propagating crack.

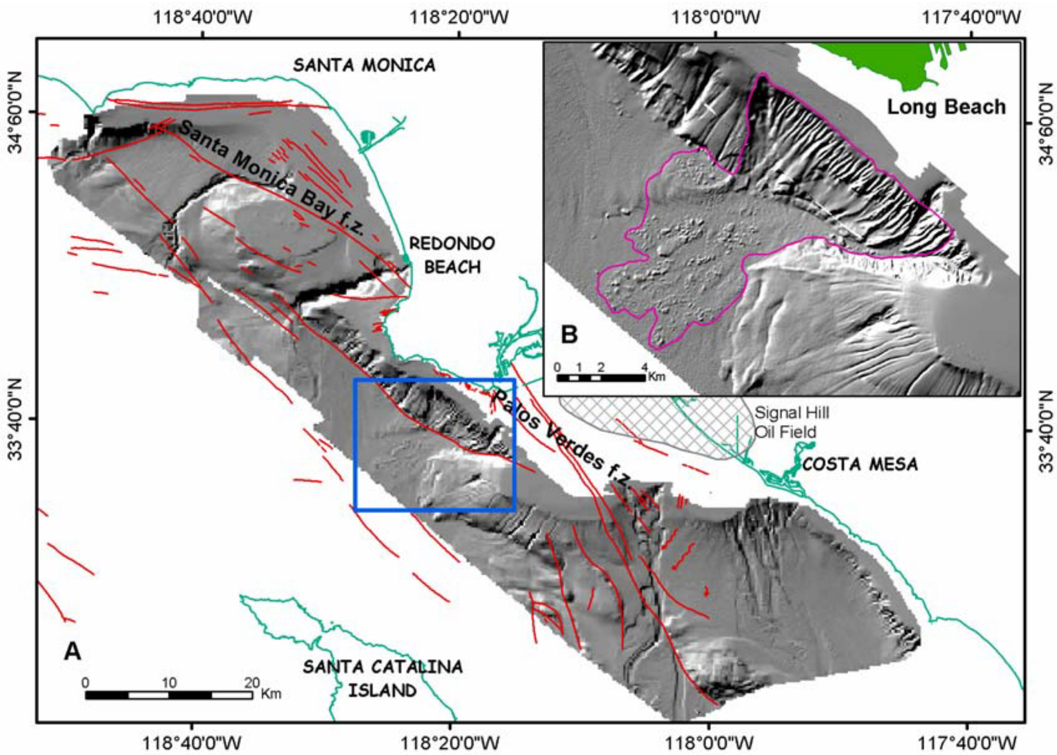

Figure 9. USGS multibeam bathymetric mosaic constructed from three different data sets (EM300, 30 kHz; EM1000, 95 kHz; EM3000, 300 kHz bathymetry) showing extensive mass wasting along the Santa Monica Bay-Long Beach margin. A) Multibeam bathymetry image with fault traces and location of the Signal Hill Oil Field. B) Expanded view of Palos Verdes rock debris avalanche deposit and gullied head scarp.

5. DISCUSSION

A diverse and complex fabric of mass wasting features exists along the active tectonic margin of California. From our studies we have determined that many submarine landslides occur along faulted continental shelves and slopes and within submarine canyons. Each of the three areas that we report upon here are commonly subjected to earthquakes, are near producing or potential hydrocarbon basins where past or present gas and oil seeps have been reported or near where fresh water aquifers crop out on the seafloor. Mass-movement features identified in the multibeam bathymetry data appear to be of differing geomorphologic ages and this relationship has been used to estimate general ages of failures. For example, modern failures have sharp relief or appear geomorphologically youthful while more subtle relief features appear older or geomorphologically mature.

Where data exist that can be used to date failure events such as seismic reflection profiles and sedimentation rates, more accurate age estimates can be made such as was done for the eastern lobe of the Goleta slide where an age of 21.2-30.6 Ka is given. Some authors (Borrero et al., 2000) and Toppozada et al. (2002) have speculated based on modeling studies and earthquake intensities that the Santa Barbara tsunamis of 1812 was caused by a failure within the Goleta slide complex or from other slides. In support of a recent failure within the Santa Barbara Channel Lee et al. (2004) provide a date of 300 years for the failure of the Gaviota slide. In Southern California Normark et al. (2004) estimates an age of 3,500 to 7,500 years ago for the failure of the Palos Verdes debris avalanche and the modern mass movement event that occurred in Monterey Canyon during the 1989 Loma Prieta Earthquake provides evidence of recent failure within Monterey Bay.

The variety of mass-movement types range from down-dropped slump blocks (Figs. 2 and 4) to complex compound landslides such as the Goleta slide (Fig. 6) with many of these features

exhibiting multiple failure events such as observed in the different lobes of the Goleta slide and what appears to be a two-phase failure of Gaviota and the other slides in the Santa Barbara Channel. Evidence for this type of failure lies in the apparent propagating cracks that initiate at mid-slope just beneath the head scarps and areas of evacuation of these slides. This indicates that a retrogressive failure occurs with an initial mud flow down slope followed by an up slope failure. In central California the many landslides mapped there are primarily concentrated within submarine canyons and continental slope where undercutting of canyon walls appears to lead to retrogressive failures.

We assume that multiple types of mechanisms ranging from earthquakes, tectonic elevation, or oversteepening of slopes, fluid flow and sediment accumulation are responsible for the submarine landslides we studied along the California continental margin. In most cases we suspect that mass-wasting results not just from one of these mechanisms, but from multiple ones. Therefore, we speculate that areas that have experienced landslides in the past are prone to failure in the feature.

Evaluation of the differing geomorphology of mass-wasting features along the central California margin suggests that much of the landslide activity in this region have occurred during the last low-stand of sea level in the Pleistocene (ca. 18 Ka) as concluded by Normark and Gutmarker (1988) and Greene et al. (2002). Older landslides in canyon heads appear to result from the tectonic and eustatic sea level changes and undercutting by turbidity currents along canyon axes.

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