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The Santiago Landslide and Associated Ridge-top Graben (Sackungen): Implications for Paleoseismic Landslide Studies

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ABSTRACT

Some recent paleoseismic studies have focused on dating ridge-top graben deposits to evaluate the timing of paleoseismic events. By contrast, our study of the Santiago landslide demonstrates that ridge-top grabens also can be associated with aseismic, deep-seated landsliding. The Santiago landslide in Anaheim Hills, California, failed during the winter of 1992–1993 in response to elevated groundwater conditions associated with intense rainfall. The head of the active landslide included a zone of extensional deformation along the bounding ridgeline. Interpretation of historical, aerial photographs indicates that the active landslide is a re-activated, ancient, deep-seated, translational landslide and an associated ridge-top graben. Large-diameter borings within the ridge-top graben encountered thick colluvium, steeply dipping colluvium-filled fractures, and shears with normal offsets. In contrast to the rupture surface within the central part of the landslide, the basal rupture surfaces in the graben area had significantly less gouge. We interpret this contrast in gouge development as an indication that the ridge-top graben developed later than the original landslide by upslope progression of the deformation. Our limit-equilibrium, slope-stability analyses indicate that either high groundwater or seismic ground motion could have previously activated the ancient landslide and ridge-top graben. Because colluvial deposits preserved within the ridge-top graben and produced by these two different types of triggering events could be misinterpreted as representing the late Quaternary paleoseismic record, these features are not useful for paleoseismic studies unless aseismic activation can be clearly precluded.

INTRODUCTION

The Santiago landslide, located in the Anaheim Hills area of the northern Santa Ana Mountains, California (Figure 1), is an active landslide that produced extensional deformation within the adjacent part of the upslope bounding ridgeline. Initial movement of the landslide caused minor cracks in road surfaces during 1992 (Barrows et al., 1993). This was followed in January 1993 by major episodes of landslide movement following intense rainfall in December 1992 and January 1993 (Slosson and Larson, 1995). Initial investigations (McLarty and Lancaster, 1999a) concluded that elevated groundwater conditions triggered landslide movement and that the maximum displacement was approximately 1 ft (0.3 m). A zone of extensional ground cracks was mapped along the ridgeline at the head of the landslide in January 1993; these ground-crack data were incorporated into our engineering geologic map (Figure 2). Movement of the landslide and opening of the associated ridge-top graben occurred during a seismically quiescent period when groundwater levels were elevated (Barrows et al., 1993). Thus, re-activation was related to groundwater conditions associated with intense rainfall rather than strong seismic shaking.

There are several different interpretations for the origin of ridge-top grabens (sackungen). Some have hypothesized that sackungen develop by slow, gravitational deformation of ridgelines (Tabor, 1971; Varnes et al., 1989; Bovis and Evans, 1995; McCalpin and Irvine, 1995; and Thompson, 1997). Others have interpreted sackungen development as a response to loss of buttressing and to stress relief associated with late Pleistocene deglaciation (Bovis, 1982; Agliardi et al., 2001; Kellogg, 2001a; and Smith, 2001). A third hypothesis is that these grabens open in response to strong seismic shaking and ridge-top shatter (Beck, 1968; Clague, 1979; Wallace, 1984; Morton and Sadler, 1989; and Kellogg, 2001b). One argument for the seismic origin of sackungen is the abundance of these features in some regions with high rates of seismic activity (Radbruch-Hall, 1978; Hart, 2001). Several studies in the Santa Cruz Mountains of northern California following the 1989 Loma Prieta earthquake (Ponti and Wells, 1991; Nolan and Weber, 1998) reported apparent, active opening of sackungen in response to strong seismic shaking. McCalpin (1999) trenched across a ridge-top graben in central Nevada that was active during two historical

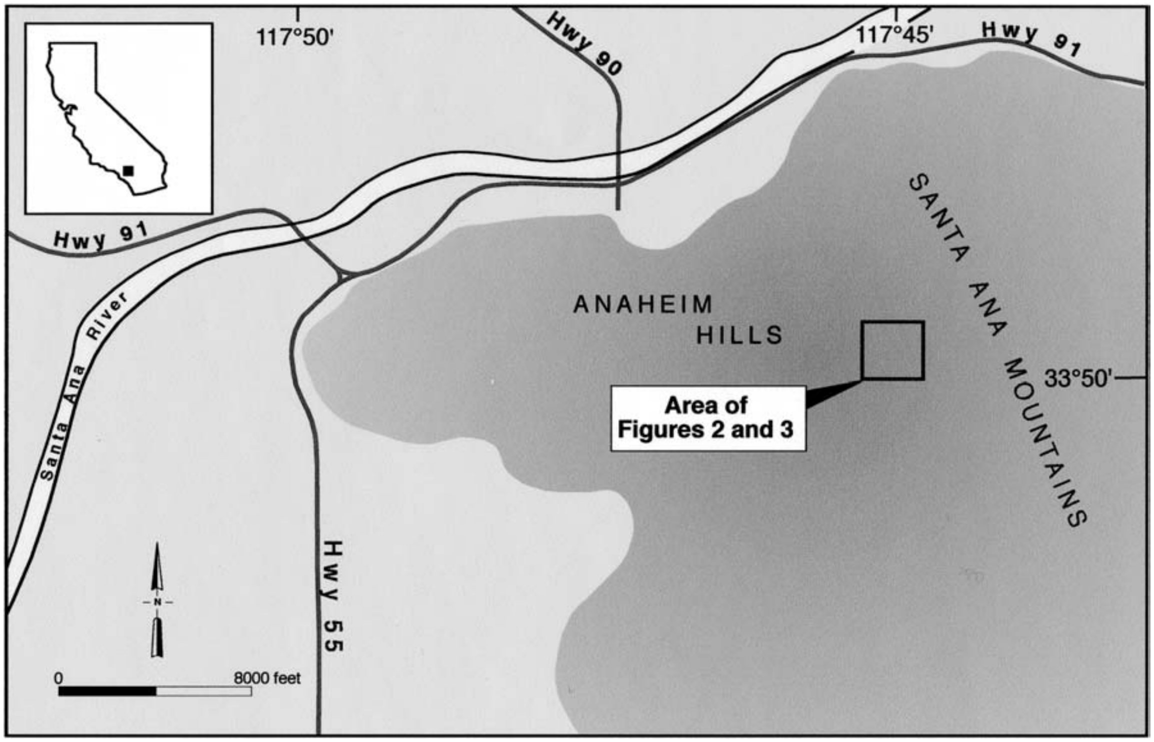

Figure 1. The Santiago landslide is located in the northern Santa Ana Mountains of southern California. 1 ft = 0.3048 m.

earthquakes and found evidence of four prehistoric, graben-opening events that the author interpreted as paleoseismic in origin. McCalpin and Hart (2001) interpreted sackungen deposits in the San Gabriel Mountains of southern California as paleoseismic in origin and compared graben-opening events with paleoseismic events recorded at nearby fault trench sites.

Jibson (1996) suggested that sackungen might be useful as paleoseismic sites only if landsliding that resulted from high groundwater can be analytically precluded. However, few studies have analytically demonstrated a seismic origin for these features. If ridge-top grabens in seismically active regions develop and activate solely in response to strong seismic ground-shaking, the in-fill deposits would indeed provide a paleoseismic record. However, if these features also activate by aseismic landsliding resulting from elevated groundwater, then their use in paleoseismic studies would be severely limited.

GEOLOGIC SETTING

The geology of the Anaheim Hills area is characterized by a northward-dipping section of sandstone and siltstone of the Miocene-age Puente Formation (Schoellhamer et al., 1981). Our field mapping of the Santiago landslide and adjacent parts of the Anaheim Hills indicates that bedding dips range from 7° to 25° to the north, and strikes range from northeast to northwest (Figure 2). The Santiago landslide apparently failed along a surface aligned roughly parallel or sub-parallel to bedding within the Puente Formation.

The Santiago landslide occurred within the Soquel Member and uppermost part of the La Vida Member of the Puente Formation. The sandstone of the Soquel Member consists of multiple, fining-upward sequences of very coarse- to medium-grained sandstone that is poorly cemented and weak; the sandstone is locally interbedded with siltstone. The siltstone of the underlying La Vida Member is interbedded with very thin beds of fine-grained, ripple-laminated sandstone. These rocks were deposited in a submarine fan environment within the rapidly subsiding Los Angeles basin during Miocene time (Critelli et al., 1995; Bjorklund et al., 2002).

Beginning in Pliocene time, compressional uplift of the Santa Ana Mountains (Gath and Grant, 2003) produced tilting of the Tertiary sedimentary section in the Anaheim Hills area. Recent mapping of a series of fluvial terraces directly west of the Anaheim Hills showed that uplift of the

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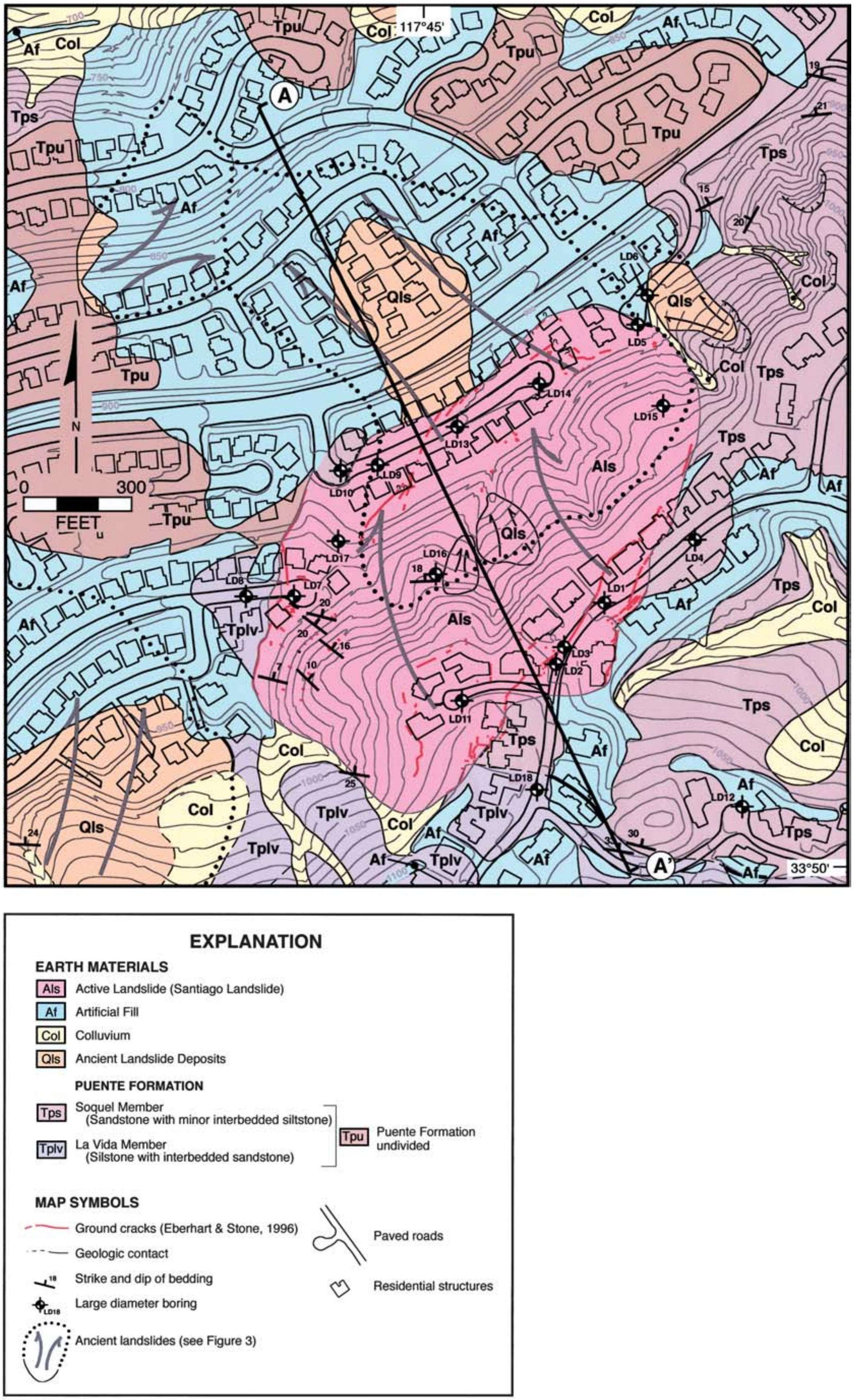
Figure 2. Geologic map of the Santiago landslide and surrounding region. Base map shows the topography during 1993 with elevations in feet above mean sea level. 1 ft = 0.3048 m.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EXPLANATION
EARTH MATERIALS
Als Active Landslide (Santiago Landslide)
Af Artificial Fill
Col Colluvium
Qls Ancient Landslide Deposits
PUENTE FORMATION
Tps Soquel Member (Sandstone with minor interbedded siltstone)
Tplv La Vida Member (Silstone with interbedded sandstone)
Tpu Puente Formation undivided
MAP SYMBOLS
Ground cracks (Eberhart & Stone, 1996)
Geologic contact
Strike and dip of bedding
Large diameter boring
Ancient landslides (see Figure 3)
Paved roads
Residential structures

Santa Ana Mountains has continued into Quaternary time (Gath and Grant, 2002). It is hypothesized that blind thrust faults are responsible for this active uplift, and that these faults might produce large-magnitude earthquakes.

Strong seismic shaking in the Anaheim Hills area results primarily from earthquakes on nearby strike-slip and thrust faults. Major earthquakes on the Elsinore and Whittier faults are capable of producing peak ground accelerations in the range of 0.39 to 0.46 g in the Anaheim Hills (Boore et al., 1997). The Elsinore fault has a recurrence interval for large-magnitude (ground-rupturing) earthquakes of approximately 200 years (Treiman and Lundberg, 2003). The Whittier fault has a recurrence interval of 760 (+640, –274) years (Working Group on California Earthquake Probabilities, 1995). Earthquakes on nearby blind thrust faults, such as the Puente Hills blind thrust system (Shaw et al., 2002), can produce peak ground accelerations in the range of 0.2 to 0.3 g in the Anaheim Hills. Dolan et al. (2003) identified at least four large-magnitude (M_w 7.2 to 7.5), Holocene earthquakes on the Puente Hills system. Because strong seismic ground shaking likely affected the Anaheim Hills area repeatedly during late Quaternary time, it could have contributed to landsliding and opening of the ridge-top graben.

Mass grading of the Anaheim Hills area during the 1970s filled drainage valleys and excavated spur ridges to develop level building pads and roads for residential development. The toe of the Santiago landslide lies within a part of the development where the topography was highly modified by grading. Although less-extensive grading was completed along the northeast-trending ridgeline at the head of the landslide, the subtlest geomorphic features were obliterated or substantially altered.

GEOMORPHIC EVALUATION

We evaluated the pre-development geomorphology by interpreting stereo pairs of historical aerial photographs. Drainage development and incision followed the uplift of the Anaheim Hills area, and several large, deep landslides failed into the incised valleys. These landslides are depicted on our photogeologic map (Figure 3). Over time, erosion and drainage incision modified the morphology of these deep landslides.

The upper part of one of these Quaternary landslides (landslide A in Figure 3) coincides with the lower part of the modern Santiago landslide. Drainage incision has dissected the body of the ancient landslide and partially obscured the morphology. However, the dissected head scarp of the ancient landslide is still clearly evident.

Directly southeast of the head scarp of landslide A, a well-developed graben with a prominent, northwest-facing scarp and more-subdued, southeast-facing scarp crosses the ridge obliquely. Between these scarps is an elongate depression that forms the axis of the graben and has a dark appearance on the aerial photographs. We interpret the dark tones within the graben as evidence of lush vegetation, perhaps grasses, that flourished in the thick colluvium that filled the depression. This contrasts with the sparser vegetation on the surrounding parts of the ridge where the soil is thin.

The head of the Santiago landslide correlates closely with the ridge-top graben that is visible in the historical aerial photographs. Based on the map relationships with landslide A and the ridge-top graben, we hypothesize that the graben developed as a result of the upslope progression of landsliding during late Quaternary time.

SUBSURFACE INVESTIGATION OF THE SANTIAGO LANDSLIDE

We conducted a subsurface investigation consisting of downhole logging of 18 large-diameter bucket auger borings drilled within the head, toe, and body of the Santiago landslide and within adjacent areas off the landslide. The boring locations are shown in Figure 2. The borings drilled within the body and toe of the landslide encountered a basal rupture surface with a well-developed gouge bounded by highly polished, striated surfaces (Figure 4). The thickness of the basal rupture gouge in these borings ranges from 0.1 to 3 ft (0.03 to 0.9 m).

By contrast, the borings within the ridge-top graben encountered a basal rupture surface with less gouge development; the thickness of the observed clay gouge ranges from 0.1 to 1 in. (0.25 to 2.5 cm). In the ridge-top graben area, numerous open fractures, colluvium-filled fractures, and steeply dipping shears with normal offsets were encountered above the basal rupture surface.

The log of boring LD-3 (Figure 5) provides a good example of the geology exposed within borings in the ridge-top graben area. In the upper 3 ft (0.9 m), the boring encountered artificial fill placed during mass grading. Below the fill is an 11 ft (3.4 m) thick deposit of colluvium. Below the colluvium, the sandstone has abundant open fractures and colluvium-filled fractures that widen upward; one of these fractures has a distinct normal offset. At a depth of 35 ft (10.7 m), the polished and striated basal rupture surface of the landslide has a relatively thin, 0.1 to 1.0 in. (0.25 to 2.5 cm) thick, clay gouge.

In boring LD-2, we encountered thick colluvium and colluvium-filled fractures up to 1.5 ft (0.5 m) wide that extend to a depth of approximately 24 ft (7.3 m). These fractures strike roughly parallel to the ridge-top graben. The fractures in the ridge-top graben area apparently filled with colluvium after earlier graben-opening events.

RAINFALL AND GROUNDWATER

The Santiago landslide and associated ridge-top graben failed during a period of intense rainfall during December

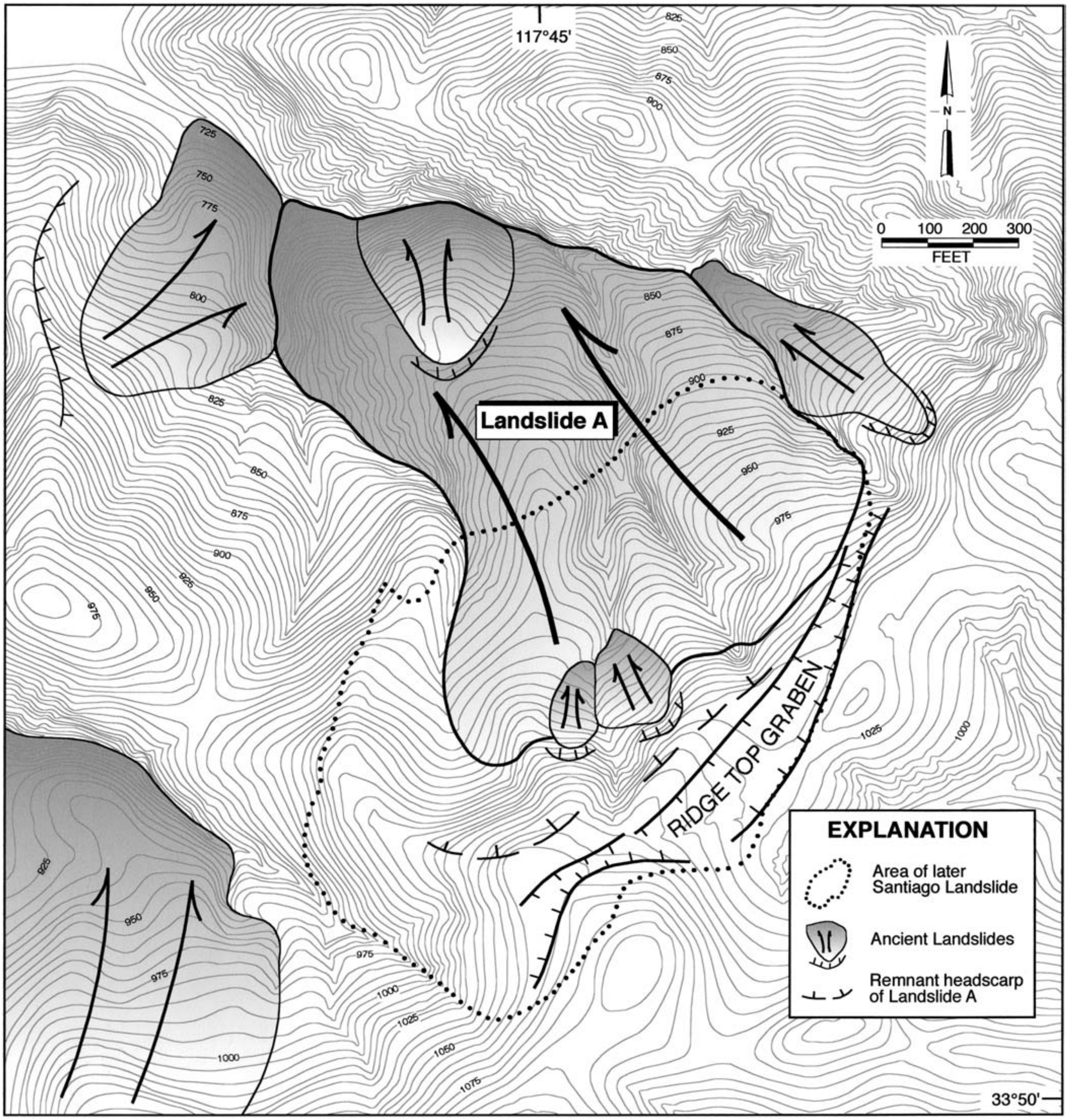

Figure 3. A photogeologic map of ancient landslides in the vicinity of the Santiago landslide. Topographic base shows conditions before mass grading. The elevations are in feet above mean sea level. 1 ft = 0.3048 m.

1992 and January 1993. Fifteen inches (38 cm) of rain, 102% of the 14.7-in. (37.3-cm) average annual rainfall for Orange County, fell during those two months (Figure 6). Rainfall during the previous year was also above average and undoubtedly contributed to elevated groundwater conditions. Figure 6 shows the yearly rainfall record for two nearby rainfall stations. Rainfall during the winter of 1992–1993 was exceptionally high when compared with the rainfall record from preceding years.

Piezometer data from Eberhart and Stone (1996) indicate that groundwater levels were elevated within the landslide mass and surrounding area at the time of failure (Figure 7). Subsequent installation of dewatering wells and horizontal drains has lowered groundwater

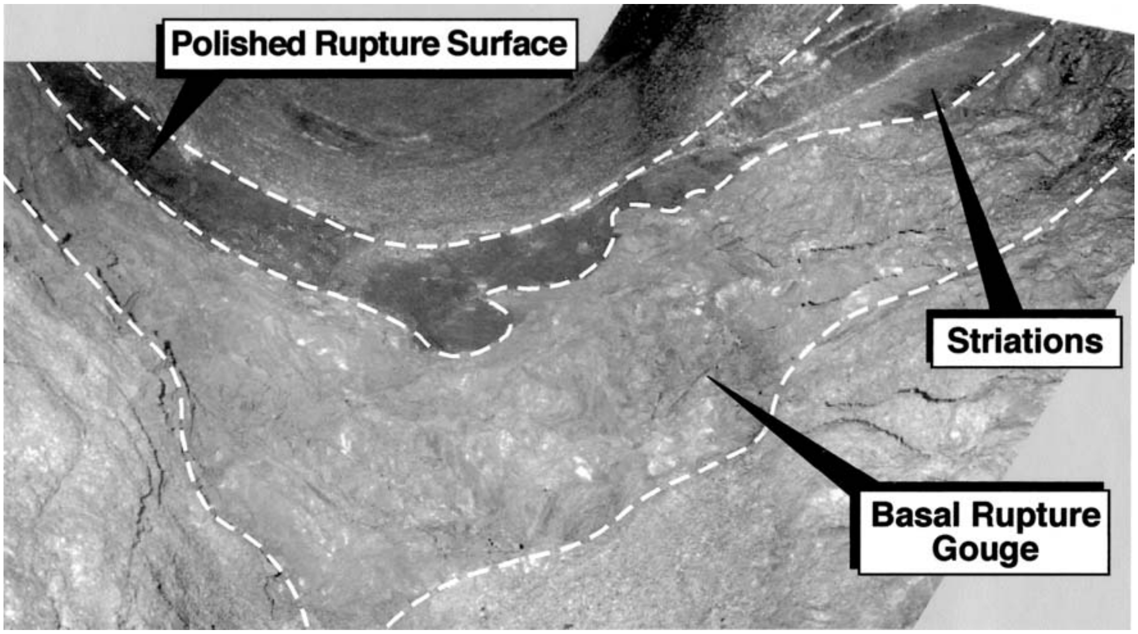

Figure 4. Photograph looking upward at the basal rupture surface of the Santiago landslide in boring LD-15 located within the central portion of the landslide. Note the polished, striated, upper-bounding surface that overlies a thick, cohesive gouge.

levels and substantially improved the stability of the landslide mass (McLarty and Lancaster, 1999b). The Santiago Landslide has not moved since completion of the dewatering system.

Little historical data are available regarding the groundwater conditions in the Anaheim Hills area before development. Early geotechnical investigations did not include installation of piezometers to evaluate the groundwater levels. Exploratory borings drilled before development were few, widely spaced, and generally shallow; most did not encounter groundwater. However, earlier investigations of the Santa Ana Mountains showed springs in the area of landslide A (Schoellhamer et al., 1954). Permeable strata that are exposed in the vicinity of the Santiago landslide can be traced up-dip through the subsurface to a south-facing, anti-dip slope where recharge occurs.

If landslides and associated ridge-top graben in the Anaheim Hills area are currently being activated during wet winters (such as 1992–1993), then it is highly likely that they would have been activated during the even wetter periods of late Quaternary time. Several paleoclimatic studies conducted in southern California have found evidence of wet periods during late Pleistocene and Holocene time. Templeton (1964, described in Stout, 1977) evaluated the latest Pleistocene rainfall history of southern California using dendrochronologic analysis of cypress samples recovered from the La Brea tar pits and concluded that average annual precipitation during a late Pleistocene wet period (14.90 ka to 14.89 ka) ranged from two to five times the current average annual rainfall for Los Angeles. Quade et al. (2003) studied wetland deposits in southern Nevada and found evidence for three late Pleistocene-to-Holocene wet periods, dated at <26.3 to 16.4 ka, 14.5 to 12.3 ka, and 11.6 to 9.5 ka, when groundwater recharge and discharge from desert springs was high. Miller et al. (2001) studied fan development of debris flow at Silurian Lake in the Mojave desert and found evidence of a wet period between 6.5 and 6.3 ka. Owen et al. (2003) dated latero-frontal moraines in the San Bernardino Mountains of southern California and found four glacial advances dated at 20 to 18 ka, 16 to 15 ka, 13 to 12 ka, and 9 to 5 ka; the authors further concluded that these glacial advances occurred during periods of increased winter precipitation and decreased summer temperatures. Clearly, the late Quaternary climate included wet periods when groundwater recharge rates were relatively high, increasing the probability of aseismic activation of deep-seated landslides and ridge-top grabens.

LIMIT-EQUILIBRIUM ANALYSES

Although the late Quaternary paleohydrologic and paleoseismic conditions that resulted in the upslope progression and graben development are not known directly from this study, we evaluated the contribution of both strong seismic shaking and elevated groundwater by performing limit-equilibrium slope-stability analysis on cross section A-A′. Specifically, we used the pre-grading profile and modeled landslide A and the ridge-top graben as a single block with a tension crack at the upslope end. These analyses were performed using three different groundwater levels (Figure 8). The highest groundwater

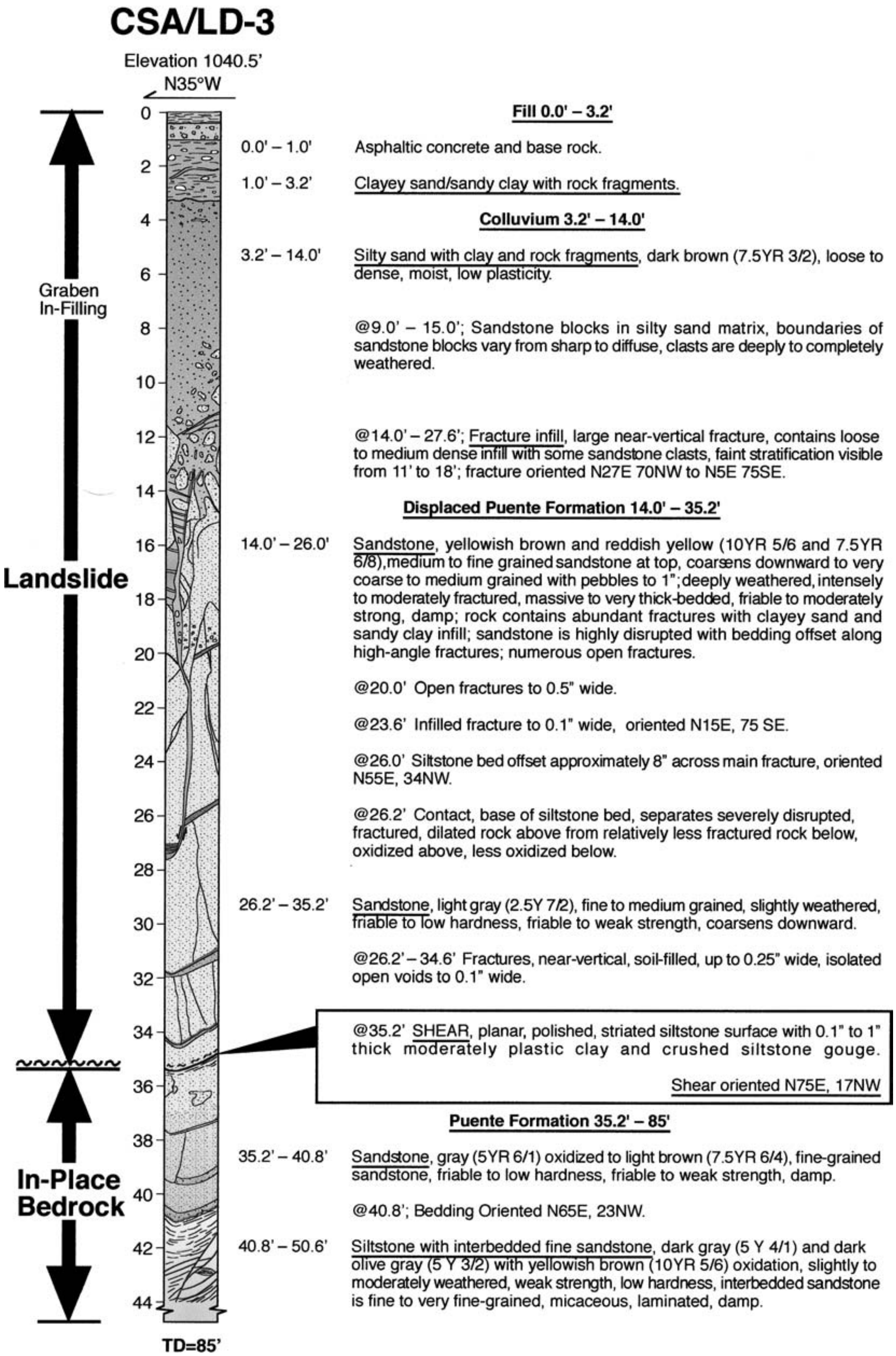

Figure 5. Log of boring LD-3 within the ridge-top graben. Note the thick accumulation of colluvium and steeply dipping, colluvium-filled fractures. 1 ft = 0.3048 m.

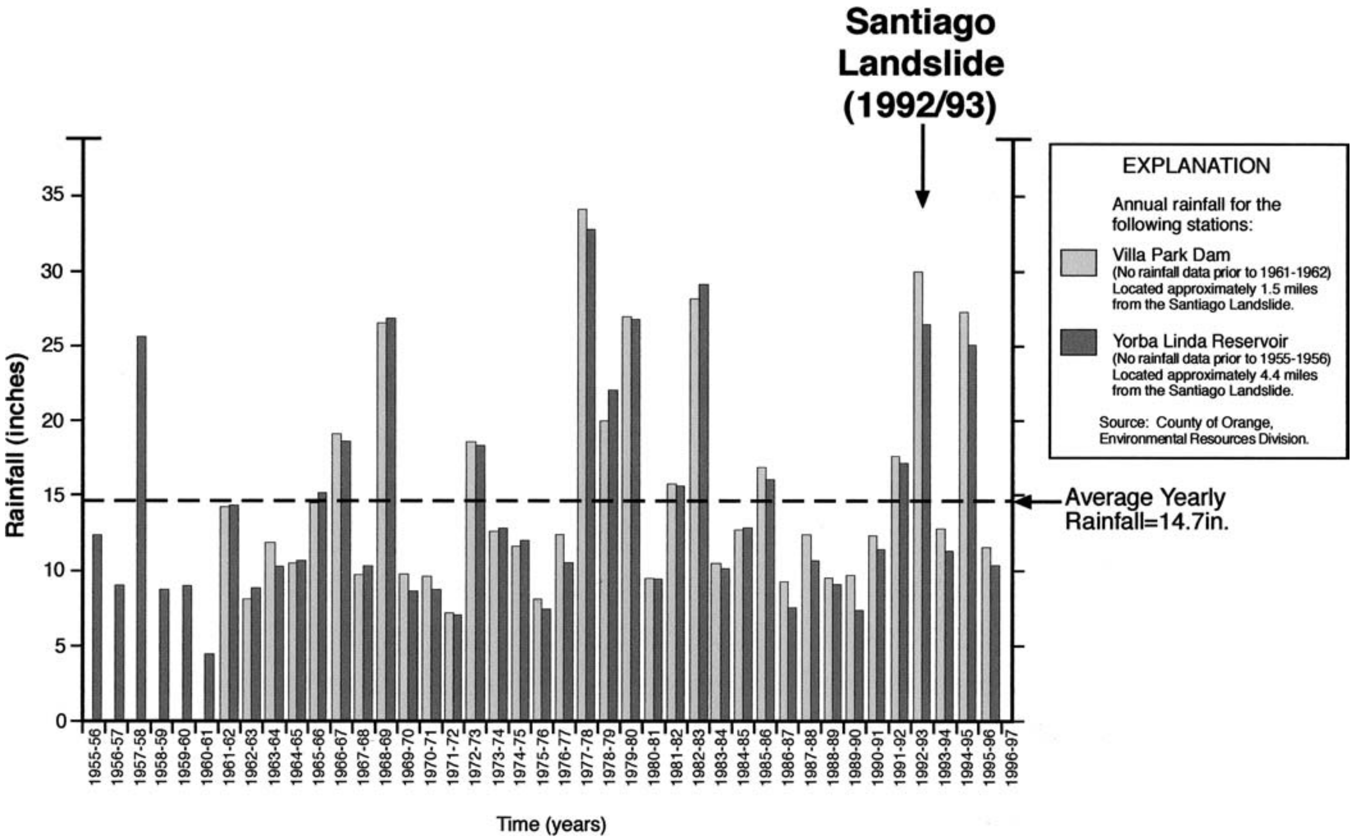

Figure 6. Rainfall records for stations located within 5 miles (8 km) of the Santiago landslide. 1 in. = 25.4 mm.

level corresponds to the level at the time of failure during January 1993. The lowest groundwater level approximates conditions during a dry period, when groundwater levels were below the rupture surface of the landslide. The third groundwater level is a hypothetical intermediate piezometric surface used to complete the analysis. To evaluate displacement resulting from seismic ground motion, we used a computer program by Jibson and Jibson (2002) that incorporates the methods of both Newmark (1965) and Bray and Rathje (1998). The seismic-displacement input-parameters are provided on Table 1, and the results of our analysis are shown on Table 2.

DISCUSSION

Our subsurface observations support the hypothesis that a well-developed, ridge-top graben is present at the head of the Santiago landslide. The presence of a thick accumulation of colluvium is not easily explained in a ridge-top setting without graben development. Open and colluvium-filled vertical fractures, as well as shears having normal displacements, also indicate a history of extensional deformation of the ridgeline.

A representative cross section (A-A′, Figure 7) shows our interpretation of the subsurface relationships between landslide A, the ridge-top graben, and the Santiago landslide. The development of a thick, basal rupture gouge in the body and toe of landslide A implies that either this ancient landslide has experienced considerably more displacement than the ridge-top graben or that the basal rupture surface followed a weak bed that thinned toward the ridge-top. The development of a thick, basal rupture gouge would require repeated displacements that would total more than the approximately 1-ft (0.3-m) maximum displacement that was recorded during the 1992–1993 event. The geomorphology of the ancient landslide that is visible in aerial photographs before development also implies that landslide A has experienced considerable, cumulative displacement. Thus, we propose a model in which landslide A originally failed without involving the ridgeline and development of the graben followed as a result of upslope progression of the landsliding. This progression likely resulted from development of a steep head scarp and loss of lateral support along the ridgeline.

Our limit-equilibrium analysis confirms that at the highest groundwater level, the landslide and graben activated, as they did during January 1993; the calculated seismic displacements at this groundwater level are large (3.2 m to 8.1 m). At the intermediate and low ground-

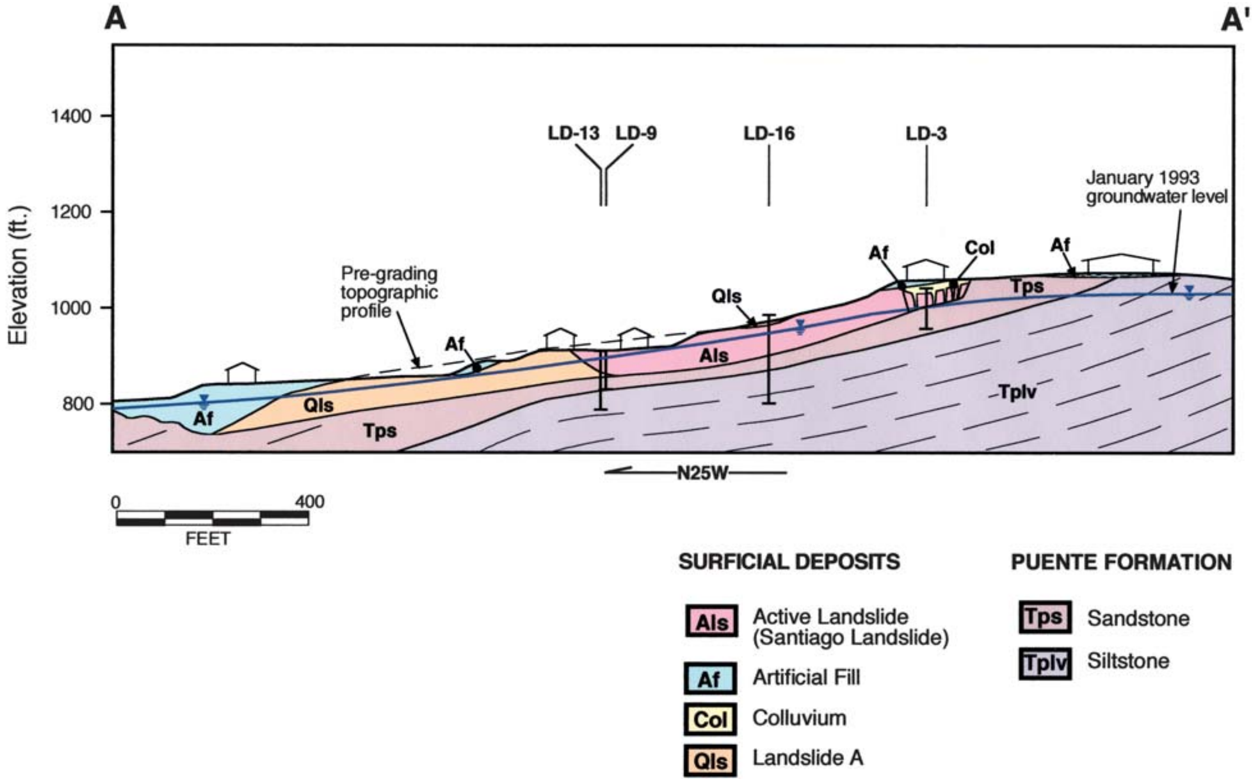

Figure 7. Cross section A-A′ illustrating the subsurface relationships between the Santiago landslide and landslide A. Also note the high groundwater levels during January 1993 when the Santiago landslide was active. 1 ft = 0.3048 m.

water levels, our analysis shows that the landslide and graben remain static unless triggered by seismic ground motion. Therefore, our analysis shows that past activation of landslide A and the associated ridge-top graben likely occurred in response to either high groundwater or strong seismic ground motion.

CONCLUSIONS AND IMPLICATIONS FOR PALEOSEISMIC STUDIES

The Santiago landslide and the associated ridge-top graben provide an example of the re-activation of a ridge-top graben by aseismic landsliding related to elevated groundwater conditions. Based on our limit-equilibrium analyses, both elevated groundwater and strong seismic shaking have likely triggered previous movement episodes of the landslide and the ridge-top graben. Colluvial wedges preserved within the ridge-top graben and produced by these very different triggering events would be indistinguishable and could be misinterpreted as representing the late Quaternary paleoseismic record. Therefore, we conclude that ridge-top graben deposits should be used to date paleoseismic events only if the potential for activation by aseismic landsliding associated

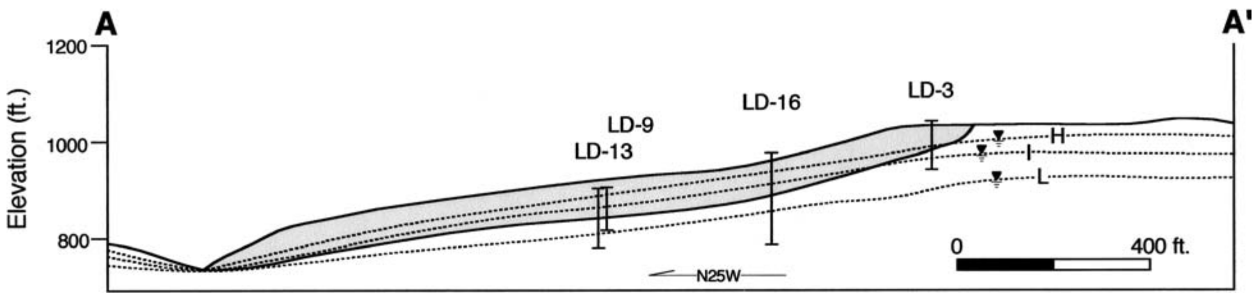

Figure 8. Generalized cross section A-A′ used for limit-equilibrium analyses. The topographic profile depicts conditions before mass grading. The static factors of safety (FS) for the three groundwater conditions are: 1.0 for high (H), 1.15 for intermediate (I), and 1.3 for low (L) groundwater conditions. 1 ft = 0.3048 m.

Table 1. *Seismic ground motion parameters.*

Fault	Distance to Fault (km)	Mw	PGA* (g)
Elsinore	6.5	6.7	0.46
Whittier	6.6	6.8	0.39

*Boore et al. (1997).

Table 2. *Seismic-displacement calculation results.*

Groundwater Level	Ky	Estimated Displacement
High	0.001	126 to 310 in. (3.2 to 7.9 m)[1] 319 in. (8.1 m)[2]
Intermediate	0.03	70 to 172 in. (1.8 to 4.4 m)[1] 34 in. (0.9 m)[2]
Low	0.055	43 to 138 in. (1.1 to 3.5 m)[1] 19 in. (0.5 m)[2]

[1]Estimated displacements by method of Bray and Rathje (1998).
[2]Estimated displacements by method of Newark (1965).

with intense rainfall and high-groundwater conditions can be clearly precluded.

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